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Developing Learning Analytics to Promote Knowledge Integration in a Technology-enhanced Learning Environment

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Developing Learning Analytics to Promote Knowledge Integration in a Technology-enhanced Learning Environment

By

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Abstract

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In a context where classrooms are becoming increasingly enhanced with technology, a research priority is to develop learning analytics and teacher dashboards that support pedagogical actions that leverage students' ideas as learning resources. While the field of learning analytics has made remarkable advances in developing and applying cutting edge technologies to support teaching and learning (e.g. machine learning-based predictive analytics), more progress is needed to connect these advances to the complex task of providing teachers with insight into student thinking (Baker et al., 2020). Additionally, the widespread adoption of the Next Generation Science Standards (NGSS) and the increased use of data-generating technologies in K-12 science classrooms makes the need for learning analytics that align with research- and theory-based pedagogy especially important. Taken together, this situation calls for the development of learning analytics and pedagogical supports that align with the current education reform efforts and leverage the unique perspectives and practices of teachers and students. My dissertation project addresses this situation by investigating the research question of how to develop and evaluate learning analytics and pedagogical supports that assist diverse teachers in supporting their students to build on their developing ideas towards integrated science knowledge.

Specifically, this design-based dissertation project uses mixed methods to develop learning analytics that support teachers in investigating their students' developing understanding of complex ideas about energy and matter transformation in photosynthesis. Using the knowledge integration (KI) pedagogical framework, I: (a) developed an online inquiry science unit on photosynthesis; (b) developed analytics to reveal student thinking by analyzing system-logged data associated with student-generated artifacts using natural language processing and machine learning techniques; and (c) developed and refined a teacher dashboard, called the Teacher Action Planner.

While this dissertation project primarily focuses on a middle school science classroom using a technology-enhanced learning environment, the resulting development strategy and products have broad application across disciplinary domains, instructional contexts, and teacher and student populations.

DEDICATION

To my father, whose legacy continues to inspire, strengthen, and comfort. I love you always, without end.

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- Professor Yannis Dimitriadis, Department of Theory of Signal and Communications and Telematic Engineering, Universidad de Valladolid
- Assistant Professor Eliane Wiese, School of Computing, University of Utah
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CHAPTER 1 - INTRODUCTION

According to the Society for Learning Analytics Research, learning analytics is "the measurement, collection, analysis and reporting of data about learners and their contexts, for purposes of understanding and optimizing learning and the environments in which it occurs" (emphasis added). Given its intended purposes, learning analytics is a promising approach for supporting teachers to attend to students' developing ideas within a technology-enhanced learning (TEL) environment. In order for teachers to understand and optimize learning and the environment in which it occurs, learning analytics (LA) must generate data that is both interpretable and actionable. While the use of data visualization principles, based on research in the information and cognitive science fields, has successfully addressed the issue of interpretability (Alhadad, 2018), developing LA that support pedagogical action, and more specifically, action that improves student learning remains a research priority. In the context of science education, that means developing LA that use students' *ideas* rather than student *behavior* as the primary data. It also means developing a dashboard to present LA in a way that allows them to function educatively to guide teachers in taking evidence-based action to support student learning. Thus, a research priority is to develop LA and teacher dashboards that support pedagogical actions that leverage students' ideas as learning resources.

Background

Inquiry learning within a TEL can support students in developing science-related knowledge and practices (de Jong, 2019; Linn, 2006; Kok, 2009). The increased use of technology during science instruction carries with it the opportunity for using the plethora of logged student data to support teaching and learning. While the wealth of student data generated within TEL environments has led to the proliferation of LA and teacher dashboards, there is a dearth of evidence for their impact. The field of LA has developed to explore the utility of using logged or otherwise captured learning data to support teaching and learning.

Research Framing

The research on LA and teacher decision-making can be seen as having two major phases. In this section, I briefly describe each research and development phase in terms of its advances and limitations.

Phase 1: Reliance on Learning-adjacent data. The first phase of LA research was driven by cutting edge data science techniques to harvest and analyze the digital traces that students left behind while engaging with educational technologies, such as learning management systems, intelligent tutoring systems, and MOOCs (Gašević et al., 2015). Phase 1 LA relied heavily on learning-adjacent data, (e.g. clickstream data, time spent on task, number of posts) to create a nuanced portrait of student behavior at both the course- and institutional-level. For reasons related to data literacy expertise, administrators, rather than teachers, were the primary users of phase 1 LA (Vatrapu et al., 2011; Means et al., 2011). Consequently, phase 1 LA became tools for predicting student success and making institutional decisions rather than supporting teaching and learning (Dawson et al., 2014).

To reduce the need for data literacy training, research and development centered on LA dashboards (Verbert et al., 2013). The dashboards developed during this phase drew on cognitive science, psychology, and human-computer interaction research to improve the interpretability of LA (Alhadad, 2018). Despite the increased interpretability, these LA dashboards were not able to support teachers in improving student learning since they presented teachers with analytics based on data that lie *adjacent* to the learning process (e.g. the number of course resources accessed, or the duration of log-in session) rather than data that lie *congruent* to and are thus reflective of the learning process (Verbert et al., 2013; Schwendimann et al., 2017). For example, Li and colleagues (Li et al., 2020) used time-stamped data associated with students' click events in an online course (i.e. clickstream data) to approximate their time management and effort regulation. The analysis of this clickstream data was used to predict students' course performance. While such analysis provides valuable information regarding learning outcomes, which are helpful to administrators for increasing system efficiencies, they do not provide teachers with insight into the learning process, which is needed to support students in understanding the course content and improving their course performance (Baker et al., 2020).

Phase 2: Developing Strategies for Supporting Classroom Use. Researchers in phase 2 addressed the issues regarding pedagogical value by adopting LA development methodologies based on participatory design (Feng et al., 2016). In these researcher-practitioner partnerships (RPP), teachers provided researchers with information regarding their specific course objectives and assessment goals to develop analytics that would give teachers the relevant information they needed to make pedagogical decisions (Tissenbaum et al., 2012; Echeverria, Martinez-Maldonado, et al., 2018; Rodríguez-Triana, Prieto, Martínez-Monés, et al., 2018). However, in many of these studies, the majority of the teacher partners had substantial teaching experience (Echeverria, Martinez-Maldonado, et al., 2018; Holstein et al., 2017, 2018). The limitation of developing LA and dashboards in partnership with primarily experienced teachers is that they are pedagogically valuable primarily for experienced teachers. Furthermore, developing pedagogically useful LA and dashboards in partnership with experienced teachers can mask the inherent limitations of these technologies, namely that they still rely on learning-adjacent data (Rodríguez-Triana, Prieto, Martinez-Mones, et al., 2018; Echeverria, Martinez-Maldonado, et al., 2018). While experienced teachers have sufficient teaching expertise to use tangentially-relevant learning data (e.g. task completion, number and duration of course resource use) to take productive pedagogical actions, teachers with less expertise may not (Holstein et al., 2017, 2018).

To support more teachers in taking analytics-informed pedagogical actions, researchers developed dashboards for LA that were aligned to pedagogical scripts. Similar to theatrical play scripts, pedagogical scripts dictate the exact role, location, action, and sequence that students need to take to successfully meet a learning objective (Fischer et al., 2013). Teachers are positioned as script managers, making adjustments in real-time as they see fit to optimize the learning environment. These script-aligned dashboards allow teachers to monitor script enactment, bringing their attention to deviations in need of correction (Tissenbaum & Slotta, 2012; Tissenbaum et al., 2012; Rodríguez-Triana, Prieto, Martinez-Mones, et al., 2018). While such dashboards support teachers in taking pedagogical action, they can encourage actions primarily aimed at getting students "back on script" (Haklev et al., 2017) rather than those aimed at supporting students to integrate their ideas. A focus on student ideas is important, because when teachers notice and respond to students' ideas as productive resources for learning, student learning improves (Robertson et al., 2016).

In the context of the increased adoption by states of the NGSS, with its call for the development of integrated, three-dimensional knowledge (National Research Council, 2013), the creation of LA and dashboards that focus teachers attention on students' ideas and their progress toward such knowledge is critically important.

My dissertation project marks a new phase of LA and dashboard research and development. It extends the phase 1 efforts by developing LA based on learning-congruent data that reflects student progress toward integrated, three-dimensional knowledge. Additionally, my dissertation project extends phase 2 research by developing and evaluating a LA dashboard that supports teachers of diverse experiences, backgrounds, and teaching practices to use the LA and take pedagogical actions that promote coherence in students' developing ideas.

Theoretical Framework

To guide the development and evaluation of LA and a teacher dashboard, I draw upon the Knowledge Integration pedagogical framework.

Knowledge Integration (KI) Framework

In keeping with socioconstructivism, the KI framework is grounded in a social constructivist perspective of learning and provides guidance for supporting students to develop integrated science knowledge. The framework holds that students enter any learning environment with preformed ideas that were developed through interactions with their physical and social environments and that inform their understanding of new ideas ((Linn & Eylon, 2011)). Unlike the learning perspectives based on conceptual change (Chi, 2008), the KI framework asserts that students' repertoire of ideas include both incomplete and complete ideas. This notion of incomplete ideas is similar to the Knowledge in Pieces perspective ((Smith III et al., 1994)), which claims that building coherent knowledge occurs over time via a mechanism of stitching together pieces of naive conceptualizations formed through personal (sensorimotor and social) experiences. The KI framework advocates for a *revise* rather than *replace* approach to supporting the development of integrated understanding (D. Clark & Linn, 2013), even when students' incomplete ideas are in conflict with one another(Disessa, 2008; Linn & Eylon, 2011; Chi, 2005). This approach reflects the perspective that students make concerted effort to make sense of their experiences (Novak & Gowin, 1984), effort that can be harnessed by science instruction to support their understanding of complex scientific concepts (Linn et al., 2003).

The idea that learning can be *designed for* is captured by the term *learning design*, around which an entire educational field has been formed (Lockyer et al., 2013). Lockyer offers the following definition of learning design: "the sequence of learning tasks, resources, and supports that a teacher constructs for students over [time, that] captures the pedagogical intent of a unit of study"(Lockyer et al., 2013, p.1441-1442). A KI-based learning design, therefore, reflects the strategy used to support students in developing integrated knowledge. Specifically, in a KI-based learning design, students' ideas are elishortcited and made available for development by supporting them to distinguish between *their ideas* and evidence related to *normative ideas*. This distinguishing step is critical for students to develop integrated knowledge as it is when students determine which ideas are most productive for understanding the phenomena under study. The distinguishing step is often the step in which students and teachers need the greatest support (Vitale et al., 2016;

Wiley et al., 2019). Students are then supported to refine their initial ideas in light of this evidence.

The KI framework espouses pedagogy that is guided by the four following tenets: (a) make thinking visible; (b) make learning accessible; (c) support learning from others; (d) support lifelong learning (Linn & Eylon, 2011). The major claim of the KI framework is that pedagogy that upholds the four tenets and engages students in the aforementioned steps will support the development of integrated science knowledge.

In this dissertation project, the KI framework functions as an overarching theoretical lens. As such, the design principles and perspectives detailed in the included studies are consistent with either the principles or tenets KI framework.

Objectives and Research Question

Recognizing the importance of addressing the aforementioned needs and challenges associated with using LA to support student learning, I set the following as my research objectives:

1. Develop LA that support teachers to understand students' developing ideas about the complex science topic of energy and matter transformation during photosynthesis and cellular respiration (see Table 0)

2. Develop an LA dashboard to support teachers in taking pedagogical actions in ways that create space for the unique perspectives and practices of teachers while helping students to develop the type of science knowledge called for by the NGSS, namely integrated, three-dimensional knowledge (see Table 1)

Research Objective 1 - Develop LA that support teachers to understand students' developing ideas about the complex science topic of energy and matter transformation during photosynthesis and cellular respiration	
Study	Research Questions
Study 1 - Mechanistic Photosynthesis Animation Design	RQ: How to design an animation aligned with the NGSS standard goal of supporting students to construct a scientific explanation of the role of photosynthesis in the cycling of matter and flow of energy into and out of organisms?
Study 2 - Mechanistic Photosynthesis Animation Classroom Evaluation	RQ: Does productive engagement with the Mechanistic Photosynthesis Animation and structured instructional scaffolds support students to develop a robust and coherent understanding of the mechanism of (i.e. how) energy and matter transformation during photosynthesis?
	RQ: Does productive engagement with the Mechanistic Photosynthesis Animation and structured instructional scaffolds support students to construct a scientific explanation based on evidence for the role of photosynthesis in the cycling of matter and flow of energy into and out of organisms (i.e. matter and energy transformation)?
Study 4 - Developing a strategy for developing and implementing LA for integrated, three-dimensional knowledge of photosynthesis	RQ: How can LA be created to provide teachers with actionable insight for supporting integrated, three-dimensional knowledge?

Table 0: The studies and associated researcher questions that align with Research Objective 1.

Research Objective 2 - Develop an LA dashboard to support teachers in taking pedagogical actions in ways that create space for the unique perspectives and practices of teachers while helping students to develop the type of science knowledge called for by the NGSS, namely integrated, three-dimensional knowledge	
Study	Research Questions
Study 3 - An RPP-based model for redesigning the WISE Photosynthesis unit	RQ: Can the KI framework guide the design of both curriculum customization and professional development?
	RQ: Which professional development activities enable teachers to use pedagogical principles to align existing curriculum materials with NGSS?
	RQ: Which professional development activities support teachers and researchers to collaborate to develop curriculum that enables students to meet the three-dimensional learning goals of the NGSS?
Study 4 - Developing a strategy for developing and implementing LA for integrated, three-dimensional knowledge of photosynthesis	RQ: How can a teacher dashboard be created to provide teachers with actionable insight for supporting integrated, three-dimensional knowledge?
Study 5 - Evaluating the Student Learning Impact of a Learning Analytics Dashboard in a co-designed photosynthesis unit	RQ: What do the LA reveal about student learning?
	RQ: In what ways does the LA dashboard support actionable insight for teachers?
	RQ: In what ways do teachers' pedagogy influence their LA-informed actions?

Table 1: The studies and associated researcher questions that align with Research Objective 2.

My reason for choosing the topic of photosynthesis as my study focus is two-fold. First, photosynthesis is a topic that students are expect to thoroughly understand, as evidenced by the progressive instruction they receive on the topic from elementary to high school. Traditionally, the focus of instruction in the elementary and middle school has not supported students in developing an integrated understanding of the phenomenon, thus magnifying students' difficulty in understanding the topic in high school (Kesidou & Roseman, 2002; Roseman et al., 2010). While the NGSS encourages the development of integrated understanding of photosynthesis throughout K-12, few instructional resources have been developed to help students meet these standards (Roseman et al., 2017).

This situation connects to my second reason, namely, my personal teaching experience. For over a decade, including time periods before and after the adoption of the NGSS, I taught photosynthesis to middle and high school students. From this experience I developed insight into the unique teaching and learning challenges that teachers and students face, respectively. This classroom teaching and learning insight together with the knowledge I have developed through doctoral studies in the learning sciences make me well positioned to address the aforementioned needs and challenges for the topic of photosynthesis.

To meet my research objectives, I conducted the following studies organized into two phases. Each study addressed several research questions related to my research objectives.

- Phase 1 - Developing and Evaluating a KI-based Learning Design

- Study 1 - Mechanistic Photosynthesis Animation Design
- Study 2 - Mechanistic Photosynthesis Animation Classroom Evaluation
- Study 3 - An RPP-based model for redesigning the WISE Photosynthesis unit

• Phase 2 - Developing and Evaluating KI-based LA and Teacher Dashboard

- Study 4 - Developing a strategy for developing and implementing LA for integrated, three-dimensional knowledge of photosynthesis
- Study 5 - Evaluating the Student Learning Impact of a Learning Analytics Dashboard in a co-designed photosynthesis unit

Conjectures

I conjecture that linking LA to curriculum components aligned with the Knowledge Integration steps could provide teachers with insight into students' progress in the knowledge integration process through the creation of learning-congruent data. There is well-established research demonstrating the power of curricular resources based on the Knowledge Integration framework to promote robust and coherent student learning ability, as measured by the integration of complex, normative science ideas (Lee & Liu, 2009; Visintainer & Linn, 2015; Vitale et al., 2016). In this way, Knowledge Integration-aligned LA could function as a methodology for learning science research (Reimann, 2016), helping to provide insight for supporting the development of integrated, three-dimensional knowledge. I further conjecture that using the KI framework to develop a LA dashboard will support teachers in taking pedagogical actions that help students develop an integrated, and three-dimensional understanding of targeted complex science concepts about energy and matter transformation.

Research Methodology

Currently, there are no solutions to address the problem of supporting teachers to use near-time data about their students' learning process and needs in ways that promote knowledge integration. The methodologies used to design LA vary based on target audience (i.e. user) and technique, and data source (Schwendimann et al., 2017); some use available click-stream data, others use student engagement data or performance data (Verbert et al., 2013). Developing and evaluating LA that support teaching and learning toward integrated science knowledge necessitates methodologies that are well suited for investigating classroom teaching and learning. Many approaches exist for investigating issues related to classroom teaching and learning, some quantitative, some qualitative, and some a hybrid of the two.

Developing implementable LA that support student learning requires an approach that can accommodate this level of complexity. Participatory design methodologies, like design-based research (DBR), provide opportunities to design customized LA to meet the unique user needs. Given its focus on pragmatic yet theory-grounded solutions, iteration, and multidisciplinary teams, DBR is an approach growing in popularity for addressing complex classroom issues, like the design and use of LA (Sandoval & Bell, 2004; Reimann, 2016). It entails the rigorous application of theoretical insight and principles of engineering design to solve complex, practice-based problems (Sandoval & Bell, 2004). Like Reimann (Reimann, 2016), we identify the centrality of theory in DBR as its primary affordance for developing LA and LA dashboards.

Drawing on design practices in the field of engineering (Collins, 1992), DBR utilizes iterative cycles of design. The problems for which DBR is employed to address arise from the dynamics of complex systems, like classroom education. Although theory can give insight toward the development of a solution, the final solution results from a process of iterative refinement in response to in situ complications during testing (i.e. informed trial and error). The value of iterative cycles of designing and testing is that it improves the efficacy of the design solution.

Additionally, DBR relies on design teams composed of individuals from multiple disciplines. The rationale is that the complexity of the problem space (e.g. classroom teaching and learning), warrants the need for a design team with diverse yet relevant expertise. No individual stakeholder, whether researcher, teacher or software engineer can develop a viable and effective LA solution independent of the other stakeholders. Researchers have knowledge about learning theories and evidence-based pedagogical structures, teachers have knowledge about the specific classroom constraints and diverse learning needs of their students, and system developers have knowledge about technical constraints and possibilities. During each design iteration, the members of this multi-disciplinary, multi-stakeholder design team contribute their ideas and perspectives. By sharing their specialized knowledge throughout the development and implementation process, the stakeholders can collaboratively develop LA that can function as compatible partners for teachers in the classroom context.

The goal of DBR methodology is to rigorously apply theoretical insight and principles of engineering design to solve complex, practice-based problems (Sandoval & Bell, 2004). In accordance with this goal, Sandoval and Bell (2004) call for the use of "embodied conjectures" that guide the development of the design solution and get reified in the solution features. These embodied conjectures derive from the relevant body of literature and from the rich discussion in which the members of the design team share their expertise, ideas, and perspectives.

Since I designed a solution that needed to work within the complexities of science classroom teaching and learning, I used a design-based research methodology. Consequently, the learning resources and LA solutions developed in this project are the product of a design team consisting of researchers, teachers, and system developers, and result from multiple cycles of design.

I also used mixed methods to gather and analyze the data needed to achieve my research goal of developing a LA dashboard that supports teachers in helping their students develop an integrated understanding of energy and matter transformation during photosynthesis.

Dissertation Outline

The remaining chapters in this dissertation proceed as follows.

- Chapter 2
  - Study 1 - Mechanistic Photosynthesis Animation Design
  - Study 2 - Mechanistic Photosynthesis Animation Classroom Evaluation
- Chapter 3
  - Study 3 - An RPP-based model for redesigning the WISE Photosynthesis unit
- Chapter 4

  - Study 4 - Developing a strategy for developing and implementing LA for integrated, three-dimensional knowledge of photosynthesis

- Chapter 5
  - Study 5 - Evaluating the Student Learning Impact of a Learning Analytics Dashboard in a co-designed photosynthesis unit

- Chapter 6: Summary and Discussion

Each chapter begins with a "Chapter Overview" and ends with a "Chapter Summary". The function of these sections is to create a unifying thread to connect the individual (and standalone) studies into a unified whole.

The studies this dissertation project consists of were conducted in collaboration with other researchers. These researchers have given me express permission to include our work in this dissertation. While the narration perspective of the studies is first-person plural, the linking text is written from the first-person singular.

CHAPTER 2 - DEVELOPING CURRICULUM RESOURCES TO SUPPORT AN INTEGRATED AND MECHANISTIC UNDERSTANDING OF ENERGY AND MATTER TRANSFORMATION

Chapter 2 Overview

Although energy is a familiar concept that pervades our everyday lives, developing an accurate scientific understanding of it can elude students at all levels of study, from elementary to post-baccalaureate. Nevertheless, the centrality of energy to almost every natural phenomenon requires that students develop an integrated understanding of energy across science disciplines. Accordingly, the new standards for science education, the NGSS, situate energy amongst the crosscutting concepts and the disciplinary core ideas and call for it to be taught at all grade levels (NRC, 2012).

There are numerous perspectives regarding what knowledge about energy students should learn, when they should learn it, and the support they need to learn it. Quinn (2014) points out that the specific knowledge about energy that students need to know depends on the science discipline. Duit (1987) suggests that teaching energy as a "quasi-material" could serve as a learning aid for students by bridging the gap between everyday macro-level energy concepts and scientific quantum-level energy concepts. However, he recommends doing so cautiously and primarily for younger students, who have not yet developed the cognitive capacity to learn abstract concepts. Metz (1997) challenges the notion that young students lack the cognitive capacity to engage in abstract reasoning. She argues that the perceived cognitive limitations of young students, such as what Lee and Liu (2009) assessed in a nationwide study of middle school students, might be a byproduct of inadequate instructional support. However, Abrams and Southerland (2001) point to the prioritization in curricula of explaining the role or purpose of the phenomena - the why rather than the how, as an additional factor to explain their observation that students have difficulty explaining how natural phenomena occur.

In contrast to the previous standards (e.g. 2000 California Science Standards, Ong et al., 2000), the NGSS performance expectation for middle school life science calls for students to construct a scientific explanation of how photosynthesis facilitates the cycling of matter and the flow of energy (NGSS, MS-LS1-6). The National Research Council framework document states that scientific explanations "explain observed relationships between variables and describe the mechanisms that support cause and effect inferences about them." (National Research Council, 2012, p. 67). Furthermore, science education researchers argue that mechanistic reasoning is critical for developing an integrated and robust understanding of natural phenomena (Abrams & Southerland, 2001; Russ et al., 2008; Krist et al., 2018). I conjecture that engaging students in instruction that includes a mechanistic presentation of photosynthesis will support them in developing a robust understanding of the phenomenon and allow them to construct a scientific explanation of how photosynthesis facilitates the cycling of matter and flow of energy in and out of organisms. I base this conjecture on numerous studies that demonstrate the ability of young children to engage in mechanistic reasoning (Grotzer, 2003; Russ et al., 2008). In this chapter, I present two studies in which I evaluate this conjecture.

STUDY 1 - MECHANISTIC PHOTOSYNTHESIS ANIMATION DESIGN

Introduction

The Next Generation Science Standards (NGSS) call for a redesign of instruction to focus students on scientific mechanisms. We[1] report on the redesign process for photosynthesis. We used design-based research methods to iteratively design a mechanistic animation for middle school science students. The NGSS focus on mechanisms reflects historical changes in biological research: a transition from describing phenomena to explaining phenomenon (National Research Council, 2012).

Prior to NGSS, standards emphasized describing photosynthesis and middle school curriculum materials reflected these standards, rarely depicting energy and matter transformation during photosynthesis (Stern & Roseman, 2004). Typically, photosynthesis is described in textbooks as a process that plants use to make glucose and oxygen from sunlight water and carbon dioxide. Students' difficulty in understanding molecular-level phenomena stems from it being unobservable with the naked eye (Roseman et al., 2010). As a result of the unobservable nature of such phenomena, experts in the molecular sciences, such as chemistry and cellular biology, heavily rely on visual representations (e.g. animations; Kozma & Russell, 1997). However, most animations of photosynthesis altogether exclude a molecular-level discussion of the mechanism governing the process (van Mil et al., 2013).

In this study, we redesigned a research-tested animation of photosynthesis that was embedded in a middle school science unit and implemented in an online learning environment (Ryoo & Linn, 2012, 2014). The goal of the redesign of the unit was to support students in developing an integrated understanding of the mechanisms of energy and matter transformation during photosynthesis. A successful student in the field test of the redesign explained how light energy is transformed into chemical energy during photosynthesis saying, "Water molecules and carbon dioxide molecules enter the plant. The light energy (photon) breaks apart each water molecule, releasing the oxygen as gas and using the hydrogen to transfer chemical energy to the energy carriers. That chemical energy is used to combine the carbon dioxide and hydrogen into glucose and water, and is stored in the glucose." This response shows that photosynthesis includes several steps, each of which involves some transformation or transfer of energy or matter. By attending to the flow of matter and energy during the photosynthesis process, this response provides a scientific explanation, meeting the NGSS performance expectation associated with photosynthesis.

Mechanistic Explanations and Assessment Boundaries

The previous standards for middle school science, such as the Life Science Standards for California (Ong et al., 2000), emphasized descriptive aspects of photosynthesis and related topics (Kesidou & Roseman, 2002; Roseman et al., 2010) supported students in understanding the overall process and goal of photosynthesis. To illustrate, a successful 7th grader before NGSS, might provide the following statement, "In plants, there are energy factories called chloroplasts. They collect energy from the sun and use carbon dioxide and water in the process called photosynthesis to produce sugars." This student response would have met most other states' science standards in

[1] I switched to the first-person plural here and throughout the remainder of this chapter, excluding the Chapter Summary, as an acknowledgement of the collaborations that informed the studies presented herein, namely Eliane Wiese and Marcia Linn.

2000. This response indicates that the student knows that "energy entering ecosystems as sunlight is transferred by producers (plants) into chemical energy through photosynthesis" (previous California 6th grade life science standard). However, this response falls short of meeting the NGSS. To meet the middle school life science NGSS, the student's response would additionally need to highlight the cycling of matter and the flow of energy. To do so, they would need to describe photosynthesis as a process consisting of a series of chemical reactions that require an input of energy to rearrange the input molecules (i.e. carbon dioxide and water) into the output molecules (i.e. glucose and oxygen). They would also need to describe how energy is transferred and transformed (i.e. the flow of energy) during this process (NGSS, MS-LS1-6). Specifically, the NGSS middle school life science performance expectation calls for students to construct scientific explanation of how photosynthesis facilitates the cycling of matter and the flow of energy (NGSS, MS-LS1-6):

> Construct a scientific explanation based on evidence for the role of photosynthesis in the cycling of matter and flow of energy into and out of organisms. Clarification Statement: Emphasis is on tracing movement of matter and flow of energy.

The NGSS introduces a dilemma by establishing an Assessment Boundary: Assessment does not include the biochemical mechanisms of photosynthesis. Thus, the NGSS calls for mechanisms yet excludes them for photosynthesis in middle school.

Why? According to the National Research Council framework document, the assessment boundaries "serve two purposes: (1) to delimit what level of detail is appropriate and (2) to indicate what knowledge related to a core idea may be too challenging for all students to master by the end of the grade band" (National Research Council, 2012). The NGSS assessment boundary clarifies that the photosynthesis standard does not require instruction of the associated biochemical mechanisms. The rationale for excluding these mechanistic details from middle school instruction seems to reflect the belief that middle school students are not cognitively ready to understand, at a mechanistic level, the complexities of science concepts like energy and matter transformation (National Research Council, 1996). This view also manifests in the NGSS boundary assessment for the photosynthesis standard which discourages a mechanistic presentation of photosynthesis. Yet, leaving out those mechanisms will likely prevent students from constructing a scientific explanation that would meet the definition provided in the framework document. Thus, we sought to explore ways to communicate the mechanism so all students could benefit.

Value of mechanisms. Abrams and Southerland (2001) observed that students have difficulty explaining how natural phenomena occur. They attributed this difficulty in part to the prioritization in curricula of explaining the role or purpose of the phenomena in terms of its benefit rather than the cause, stated differently, the why rather than the how. For example, the 2000 California standards for middle school science (Ong et al., 2000) focused on the names of the inputs and outputs (e.g. light, water, glucose, etc.), the cellular location of the process (i.e the chloroplast), and its overall purpose (i.e. to store energy for the plant). This type of curricular instruction not only de-prioritizes an understanding of how photosynthesis occurs, it also allows students to maintain a naïve assumption about the photosynthesis reaction: that light (perhaps in combination with carbon dioxide and water) becomes glucose (Ryoo & Linn, 2014; Keleş & Kefeli, 2010; Marmaroti & Galanopoulou, 2006). Similar to Anderson et. al (1990), we hypothesize that these assumptions persist because middle school students are not taught how the energy and matter inputs of photosynthesis transform during the process.

The National Research Council framework document for the NGSS provides insight into the committee's definition of scientific explanation:

> "Scientific explanations are accounts that link scientific theory with specific observations or phenomena—for example, they explain observed relationships between variables and describe the mechanisms that support cause and effect inferences about them." (National Research Council, 2012, p. 67)

This definition of scientific explanation incorporates mechanistic reasoning, which science education researchers argue is critical for developing an integrated and robust understanding of natural phenomena (Abrams & Southerland, 2001; Russ et al., 2008; Krist et al., 2018). Thus, the clarification statement for the NGSS photosynthesis standard encourages instruction that allows students to trace the movement of matter and flow of energy. Taken together, it follows that the ideal instruction would include exploration of the mechanism of photosynthesis. In most states, however, the mechanistic details of energy and matter transformation during photosynthesis are delayed until high school.

We conjectured that engaging students in instruction that includes a mechanistic presentation of photosynthesis will support them in developing a robust understanding of the phenomenon and allow them to construct a scientific explanation of how photosynthesis facilitates the cycling of matter and flow of energy in and out of organisms. We base this conjecture on numerous studies that demonstrate the ability of young children to engage in mechanistic reasoning ((Grotzer, 2003; Russ et al., 2008; Krist et al., 2018). Developing such instruction would fill a gap in current curriculum materials (Kesidou & Roseman, 2002; Roseman et al., 2010; Abrams & Southerland, 2001). Moreover, such instruction would meet the needs of the many students in states where NGSS has been adopted.

Research Question

To resolve the dilemma raised by the NGSS Assessment Boundary, we explored how to design an animation aligned with the NGSS standard goal of supporting students to construct a scientific explanation of the role of photosynthesis in the cycling of matter and flow of energy into and out of organisms. To address this research question, we first reviewed online photosynthesis animations as well as published research on photosynthesis using animations to determine if they align with NGSS. Second, we identified research-based design principles that could guide the design of an effective animation. Third, we used think-alouds and classroom testing to determine how students interpreted the animation we designed based on these principles.

Existing Photosynthesis Animations

We examined photosynthesis animations available online and in published reports using criteria based on the NGSS performance expectations for photosynthesis (MS-LS1-6).

Evaluation Criteria

We developed evaluation criteria to determine if available animations:

- Target complex ideas of energy transfer and matter cycling.

- Depict the mechanism of energy and matter transformation. The mechanism needs to be understandable with minimal (6th-grade) science knowledge.
- Support students to develop a robust and coherent understanding of the mechanism of energy and matter transformation during photosynthesis, as indicated by a presentation of:
  - the inputs and outputs of photosynthesis, and
  - how matter is needed for energy transfer and transformation and energy is needed for matter transfer and transformation.
- Depict how photosynthesis mediates the cycling of matter and flow of energy into and out of organisms.

Online Photosynthesis Animations

To identify online photosynthesis animations, we conducted an internet search simulating the process a middle school science teacher might take to find a photosynthesis animation to supplement instruction. Specifically, we used the search phrase "photosynthesis animation middle school" in the YouTube and Google search engines. We explored the first 20 animation links from the YouTube search result and the first 6 Google search results (most were collections of animations, from which we examined 35 animation links. Of these 55 total links, 7 were nonfunctional, 7 were not about photosynthesis, and 4 were not animations.

We applied our evaluation criteria to the remaining 37 animations and found: 14 animations required prior knowledge beyond the middle school level (e.g., they referred to concentration gradients, electron exshortcitement, electron transport chains, etc.). Of the remaining 23 animations, only one included any mechanistic aspect of the photosynthesis process (it depicted water splitting). However, that animation did not show the quantities of the inputs or outputs and did not show the atoms and molecules in a way that allowed the viewer to track them throughout the process. While many animations included the chemical reaction for photosynthesis, or explained what the inputs and outputs were, this search revealed a lack of animations depicting the process of photosynthesis at a level appropriate for middle school students. Our search aligns with the analysis of existing molecular-level animations of photosynthesis conducted by (van MIL et al., 2016) who concluded that the available resources include either too much or too little complexity.

In our analysis of the published research, we did not identify an existing animation that could support middle school students to develop a sophisticated understanding of energy and matter transformation in photosynthesis. However, we chose the WISE Photosynthesis Animation, developed by Ryoo and Linn (2012), as the best starting point for the design process for this study.

Photosynthesis Animation Research

We selected the WISE Photosynthesis Animation (Ryoo & Linn, 2012) because it features an intermediate-level animation of photosynthesis targeted to middle school students (see Figure 1).

It depicts the molecular inputs and outputs of photosynthesis in quantities that match the standard chemical equation. Further, it shows the rearrangement of atoms in a way that allows the viewer to track individual atoms and see that matter is conserved. A classroom study conducted by Ryoo and Linn (2012) demonstrated the success of this animation compared to static diagrams in helping students develop a coherent understanding of the complex science concepts of energy

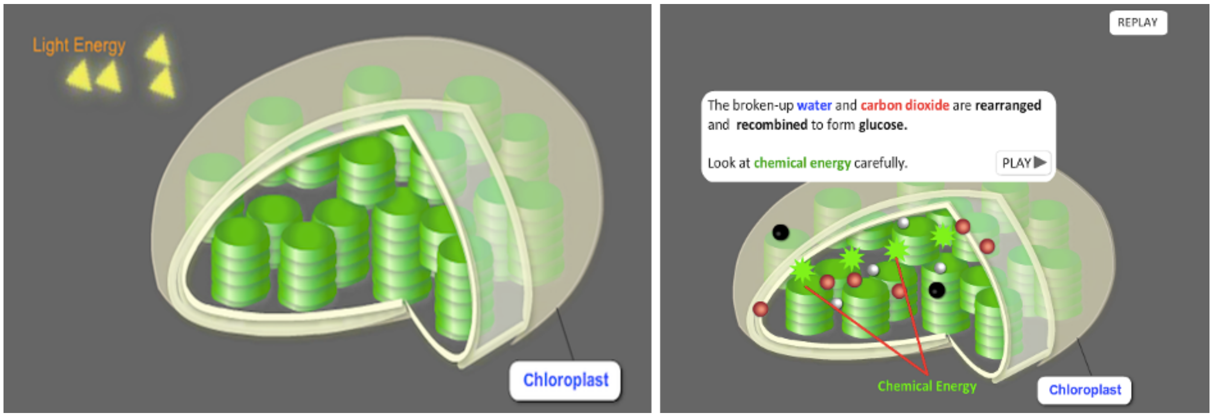


Figure 1: Screenshots from the WISE Animation. Left: light is about to enter the chloroplast, where carbon dioxide and water are gathering. When the light hits the carbon dioxide and water molecules, they will split into individual atoms. Right: glucose is formed from the constituent atoms of carbon dioxide and water. Two atoms of oxygen, not needed for glucose, are about to bond and form oxygen gas. The green stars above the chlorophyll symbolize chemical energy, which is about to enter the glucose.

and matter transformation. Another study (Ryoo & Linn, 2014) showed that the animations were sufficiently clear to support students in generating their own explanations for each step rather than relying on instructional scaffolds. These studies also revealed limitations in students understanding of the energy transformation process. While students were able to state that light energy is transformed into chemical energy during photosynthesis, they were unable to describe how this happened. This finding is unsurprising since the animation did not depict the mechanism of this transformation. In addition, the study results suggest that this animation permitted students to develop or maintain the common non-normative idea that light becomes glucose during photosynthesis.

These findings for the WISE Photosynthesis Animation suggest that students could potentially develop a sophisticated understanding of energy and matter transformation if they could see and explore these concepts in an animation. By "sophisticated understanding" we mean one that integrates an understanding of the nature of energy and matter transformation with an understanding of the photosynthesis reaction. This definition aligns with the NGSS description of a scientific explanation: linking "scientific theory with specific observations or phenomena" (National Research Council, 2012, p. 67). Therefore, we sought to design an animation to target complex photosynthesis ideas by depicting mechanisms of energy and matter transformation and require minimal (6th grade-level) science knowledge.

Initial Design Principles

We designed the mechanistic photosynthesis animation using design principles for animation design (Quintana et al., 2004; van MIL et al., 2016; Mayer & Moreno, 2003)). We aligned instruction with the Knowledge Integration (KI) framework (Linn et al., 2011) that guided the design of the Ryoo and Linn (2012) animation and principles for teaching energy (Millar et al., 2005). In this section, we describe these frameworks and principles and present a synthesized list of the design principles used in this study.

KI Pedagogical Framework

The KI framework provides guidance for supporting students to develop integrated science knowledge. It holds that students enter any learning environment with preformed ideas that were developed through interactions with their physical and social environments and that inform their understanding of new ideas (Linn et al., 2011). The KI framework calls for science learning resources that allow students' ideas to be available for exploration and further development. To accomplish this aim, the resources should make learning accessible. We adopt this tenet as an overarching guide for our design of a mechanistic photosynthesis animation.

Scaffolding Design Framework

The scaffolding design framework developed by Quintana et al. (2004) is a theoretical framework grounded, in part, in research on implementations of the KI framework in online science inquiry curriculum. It represents a synthesis of theoretical research in learning and empirical research on technology-enhanced science inquiry learning and provides theory-grounded guidelines and data-backed strategies. Quintana et al. (2004) identify students' learning needs and obstacles and offer their guidelines and strategies to support the design of software tools. We primarily drew from the scaffolding guidelines related to sense-making which calls for using representations and language that bridge students' understanding.

Multimedia Learning Design Principles

Reindl et al. (2015) developed a suite of animations, called the Virtual Cell Animation Collection, that were guided by the principles set forth by Mayer and Moreno (2003). The principles that we used for this study were:

- "Off-loading: Move some essential processing from visual channel to auditory channel.
- Segmenting: Allow time between successive bite-size segments.
- Pretraining: Provide pretraining in names and characteristics of components.
- Weeding: Eliminate interesting but extraneous material to reduce processing of extraneous material.
- Signaling: Provide cues for how to process the material to reduce processing of extraneous material.
- Synchronizing: Present narration and corresponding animation simultaneously to minimize need to hold representations in memory." (Mayer & Moreno, 2003, p. 46)

For over 5 years, I used the photosynthesis-related animations in the Virtual Cell Animation Collection to successfully teach photosynthesis at the high school level. Therefore, Mayer and Moreno's (2003) multimedia design principles strongly guided our initial design conceptions.

Mechanism Design Principles

van Mill et al. (2013) offer a framework for developing education materials that supports students in constructing molecular-level explanations of cellular behavior. The principles from this framework that we drew upon call "for educational approaches in which:

- Students are guided towards causal-mechanistic instead of functional explanations.
- Students learn how to explain machine-like protein activities from molecular interactions.
- Students are familiarized with the multiple functional levels in between cells and molecules.
- Students are familiarized with the abstract, dynamic and transient nature of molecular modules." (van Mil et al., 2013, p. 113)

Although animations provide the affordances necessary to meet this call, in a subsequent analysis of existing molecular-level animations, van Mill and colleagues (2016) concluded that the available resources include either include too much or too little complexity. This analysis corroborates our analysis of the photosynthesis animations found in internet searches. Consequently, van Mill et al. (2016) designed mechanistic education materials that provided an intermediate level of complexity by simplifying the cellular context and using a combination of cartoon-like and realistic graphics and animations of molecules and macromolecules. They tapped into students' mechanistic intuition by prompting students to attend to the causal relationships between the agents and events depicted in the animation. We were guided by the design approaches described by van Mill et al. (2013; 2016) given our goal of designing an animation to support students in developing a mechanistic understanding of photosynthesis.

Principles for Teaching Energy

To help students more accurately conceptualize energy, Millar et al. (2005) provide recommendations. First, they encourage drawing on everyday language, using terms like energy resources and fuel. Second, they suggest helping students think about events and processes in energy terms by asking questions like, "Where is energy stored at the beginning and end?" We used these recommendations in our animation design to guide our presentation of the disciplinary ideas.

Synthesis of Design Principles

We synthesized and grouped the previously described frameworks and principles into two categories, animation design principles and molecular-level explanation design principles. We use the animation design principles to guide the non-science aspects of our mechanistic photosynthesis animation and the molecular-level explanation design principles to guide the science-aspects.

Animation Design (AD) Principles

1. Present only relevant information
2. Divide information into small, successive segments
3. Synchronously engage multiple sensory modalities
4. Provide cues for how to process the information/action

5. Introduce the names and characteristics of components

Molecular-level Explanation Design (MED) Principles

1. Use representations and language that bridge students' understanding
2. Highlight key events and processes in terms of energy
3. Guide towards causal-mechanistic relationships
4. Present molecular interactions in terms of machine-like activities
5. Present molecular complexes as functional modules that are abstract, dynamic and transient in nature

Methods

To create the animation, we drew upon design-based research principles. Design-based research (DBR) can be characterized by four features: 1.) multi-disciplinary design team, 2.) designs informed by theory-grounded conjectures, 3.) iterative design cycles, and 4.) a contribution of new, empirically based, design principles.

Diverse Design Team

DBR calls for design teams composed of individuals from multiple disciplines (Collins, 1992)). The complexity of the problem space (e.g. classroom teaching and learning) warrants the need for a design team with diverse yet relevant expertise. Consequently, we formed a partnership that included classroom teachers, students, education researchers, content experts, and software engineers to design and test a mechanistic photosynthesis animation for middle school students.

Theory-informed Design Conjectures

A stated goal of design-based research methodology is to rigorously apply theoretical insight and principles of engineering design to solve complex, practice-based problems (Sandoval & Bell, 2004). In accordance with this goal, Sandoval and Bell (?) call for the use of "embodied conjectures" that guide the development of the design solution and get reified in the solution features. These embodied conjectures are derived from the relevant body of literature and from the rich discussion in which the members of the design team share their expertise, ideas, and perspectives. For this design study, we drew upon the Knowledge Integration pedagogical framework (Linn et al., 2011), the scaffolding design theoretical framework (Quintana et al., 2004), mechanistic animation design principles (van MIL et al., 2016), and instructional design principles for teaching the complex topic of energy (Millar et al., 2005). These literature-based theories and perspectives guided the efforts of the design team to develop the first iteration of the mechanistic photosynthesis animation.

Iterative Design Cycles

The use of iterative design cycles in DBR stems draws upon design practices in the field of engineering (Collins, 1992). The problems for which DBR is employed to address arise from the dynamics of complex systems, like classroom education. Although theory gives insight toward the development of a solution, the final solution results from a process of iterative refinement in response to in situ complications during testing (i.e. informed trial and error).

During each design iteration, the members of our multi-disciplinary, multi-stakeholder design team contributed their ideas and perspectives. The education researchers, content experts, and software engineers engaged in numerous design cycles prior to testing with the students and teacher design members. These pre-testing cycles took place during weekly meetings in which the first and second author presented drafts of the animation features to the education researchers, content experts, and software engineers for discussion and feedback. There was substantial discussion related to two topics, 1.) the use of analogies, and 2.) the inclusion and representation of the function of complex molecular machinery such as ATP synthase and the photosystems. Regarding the use of analogies, the education researchers expressed concern about whether the analogies would be an asset or a liability in terms of supporting student understanding. Regarding the inclusion and representation of complex molecular machinery, several members of the design team expressed concern that presenting these components would make the animation too complicated and thus inaccessible for middle school students. Using the synthesized design principles, the first and second author revised the drafts until a functional prototype of the animation was developed for testing.

Design Testing

Pilot Testing. To pilot test the new animation, we partnered with six, 8th-grade students and one, 7th-grade teacher, all of whom were familiar with the animation used in the Ryoo and Linn study (2012). The students were incentivized by their teacher with assignment extra credit to partner with us for pilot testing.

Pilot Testing Protocol. In a one-on-one semi-formal interview students viewed an initial version of the animation and were asked to describe the process being depicted in detail. They were then asked to comment on the clarity of the animation and its appropriateness for 7th-grade students.

In a semi-structured interview, the teacher was asked to review the animation in light of her plans for instruction. She was asked to evaluate the cognitive appropriateness of the animation for her student population and for 7th-graders in general. Additionally, she was invited to give feedback about aspects of the animation she would like to add or remove.

Field Testing. To field test the new animation, we partnered with a 6th grade teacher at a different middle school than our pilot testing school. For the field test, we embedded the new animation as a video with playback controls in an online science inquiry unit similar to the one used in the Ryoo and Linn (2012) study (`https://wise.berkeley.edu/project/19535#/vle/node7`). Unlike the pilot testing teacher, our field-testing teacher was not familiar with the Ryoo and Linn (2012) animation or the associated inquiry unit.

The field test took place during three class periods. I conducted a classroom observation and informally interviewed the teacher and select students. At the beginning of each class period, I invited the students to provide feedback regarding any aspect of the animation. I then conducted informal follow up student interviews with the students who volunteered feedback. The interviews were captured in written notes or audio recordings. I conducted and audio recorded the informal interview with the teacher at the end of the last class period.

New Design Principles

This research took advantage of iterative cycles of designing and testing to improve the efficacy of the design solution and refine the initial design conjectures (Sandoval & Bell, 2004). Extrapolating new design principles from the challenges and outcomes of the empirical testing informs further development. After testing the initial design with our partner teacher and students, the educational researchers, content-experts, and software engineers met to reflect on the testing results, make design revisions, and develop new principles for designing middle school-level, mechanistic animations.

Content Starting Point

To develop an animation that supports middle school students in developing a mechanistic understanding of energy and matter transformation during photosynthesis, we built on several features of the Ryoo and Linn (2012) animation. This animation showed the inputs and outputs of photosynthesis based on the standard chemical equation, as well as simplified energy and matter transformations that illustrated the process (Figure1). Specifically, it depicted:

- a simplified subcellular environment
- carbon dioxide, water, glucose, and oxygen gas molecules using atom-level icons
- atomic rearrangement as the way carbon dioxide and water form glucose and oxygen gas
- the principle of matter conservation by using accurate numbers of atoms and molecules and presenting them so that the viewer can track them

Results

Implementation of Design Principles

We implemented the Animation Design principles and the Molecular-Level Education design principles extracted from the literature (Table 1) to create the mechanistic photosynthesis animation (`https://wise.berkeley.edu/preview/unit/23276/node7`).

AD Principle 1: Present only relevant information. The photosynthesis process relies on numerous other process, at the organismal and cellular levels. At the organismal level, plants use openings in their leaves, called stomata, to take in and release gasses such as carbon dioxide, water vapor, and oxygen. They also take in water from the soil using their roots. At the cellular level, plants rely on numerous organelles and molecular complexes (e.g. Golgi apparatus, microtubules, and ribosomes) to make and transport key components of the photosynthesis process. Although these structures and components facilitate photosynthesis they are not directly related to the process. Therefore, we decided to focus the animation content on the photosynthesis process alone.

AD Principle 2: Divide information into small, successive segments. The design team, in particular the chemistry experts, identified four steps in the photosynthesis process that, if depicted concretely, could illustrate key aspects of the mechanism for energy and matter transformation. Therefore, we designed the animation to depict several molecular interactions and chemical reactions that would capture the key mechanistic moments in photosynthesis where energy is transformed and transferred. (Note: We use the concept of energy transference to refer to the induction of one entity into a high energy state through interactions with an entity in a higher energy state.

Table 1. Description of the design principles used to develop the Photosynthesis Mechanistic Animation with examples of implementation. Note: Animation Design Principle (AD); Molecular-level Explanation Design (MED)

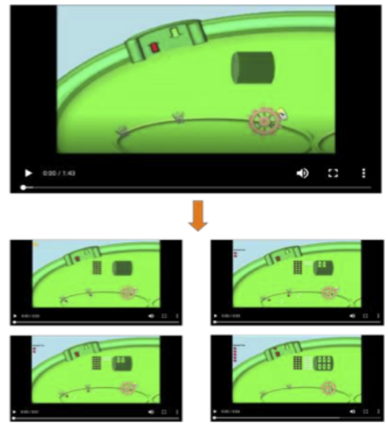
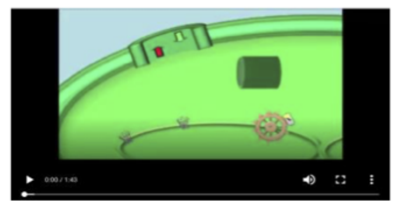
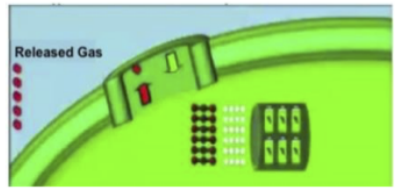
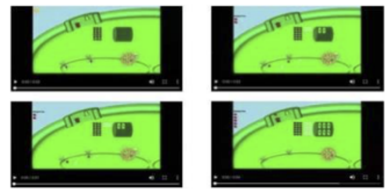
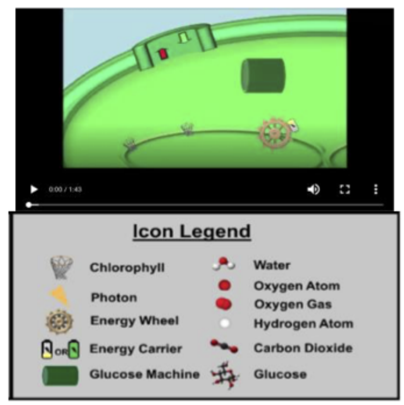
Design Principles	**Feature** (*rationale*)	**Image/Example**
Divide information into small, successive segments (AD-2)	● Video clips derived from full animation (*highlight and differentiate each of the 4 key mechanistic moments*)	
Provide cues for how to process the information or action (AD-4)	● Playback and navigation controls for the full animation and video clips (*students can watch any portion of the animation or clips as desired*)	
	● Initial and Reflection Explanation (*allow students to synthesize their understanding of the animation before and after engagement with the video clips and guiding questions*)	Initial Explanation: "What does this video show about the flow of energy through the photosynthesis process?" Reflection Explanation: "Now that you've thought about it more, revise your answer…"
	● Guiding questions for each clip (*help students to track energy through the process, attend to the relationships between agents and events, and identify causal connections*)	Clip 1: Photons are light energy. In the video, the photon disappeared. What happened to the energy? Clip 2: Where did the energy wheel get the energy to turn? Clip 3: What happens to the movement energy from the energy wheel? Clip 4: After glucose is made, why are the energy carrier molecules low energy instead of high energy molecules?

Table 1 (Continued)

Provide cues for how to process the information or action (AD-4) Highlight key events and processes in terms of energy (MED-2)	• Text (*indicate oxygen gas released from the cell*) • Alignment of atoms and molecules (*signify molecular proportionalities in the reaction*)	
Present only relevant information (AD-1) Guide towards causal or mechanistic relationships (MED-3)	• Four video clips focused on events involving energy transfer or transformation (*help students "see" the role and importance of energy in process*)	
Use representations and language that bridge students' understanding (MED-1) Introduce the names and characteristics of components (AD-5) Present molecular interactions in terms of machine-like activities (MED-4) Present molecular complexes as functional modules that are abstract, dynamic and transient in nature (MED-5)	• Analogy-based representations (*represent the key agents and mechanisms in the process in easily understood way*)	

We use the concept of energy transformation to refer to a change in the manifestation of a high energy state that is triggered by an energy transference event, e.g., from movement to bonding.)

- Transfer of Energy from Photon: Energy transfer from light to chlorophyll - a photon of light hits the chlorophyll and disappears as the chlorophyll vibrates. This event signifies the transference of energy from the photon of light to the chlorophyll.
- Splitting of Water: After the chlorophyll vibrates, the nearby water molecule separates into its component atoms, two hydrogen and one oxygen. This event signifies the transference of energy from the chlorophyll to the water. It also shows how an input of energy is needed to transform matter.
- Transformation of Kinetic Energy to Chemical Energy: The hydrogen ions/atoms from

the split water molecules flow to an apparatus causing it to move and create high energy molecules. This event signifies the transformation of kinetic energy to chemical energy.

- Production of Glucose: The high energy molecule and hydrogen atoms move to another apparatus where they react with carbon dioxide to form glucose. This is another example that shows that an input of energy is needed to transform matter.

AD Principles 3 and 4: Synchronously engage multiple sensory modalities; Provide cues for how to process the information/action. In addition to visually presenting the process of photosynthesis, we also included sound effects. These sound effects simulated the depicted action, such as an explosion for the splitting of water. In this way, the intent and function of the depicted action could be more easily understood than simply rely on a visual presentation.

AD Principle 5: Introduce the names and characteristics of components. We created an icon legend to accompany the animation that we placed directly above the animation (Figure 2). In this way, students could familiarize themselves with and easily reference the names and images associated with each component of the animation.

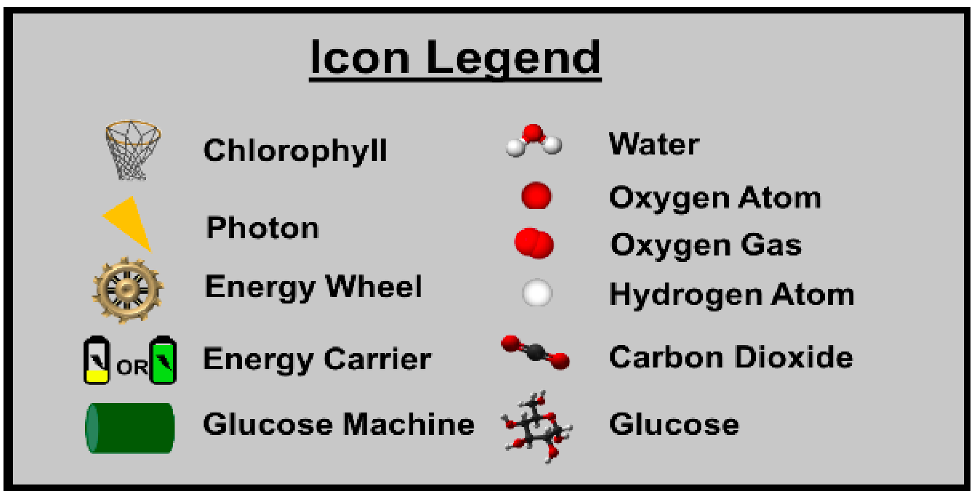


Figure 2: Icon Legend for the Mechanistic Photosynthesis Animation.

MED Principle 1: Use representations and language that bridge students' understanding. Designing the mechanistic photosynthesis animation with a close-up perspective of the chloroplast allowed us to depict the key mechanistic agents of the photosynthesis process like Photosystem II, Adenosine Triphosphate (ATP), and ATP synthase. Although these complex macromolecules are central to understanding the mechanism of energy and matter transformations during photosynthesis, the complexity and unfamiliarity of their names would likely create a learning obstacle for middle school students. Therefore, instead of using the scientific names, we used names that conveyed their function as it relates to energy: we called ATP "energy carrier"; we called ATP Synthase "energy wheel" and simplified the photosystems down to their most familiar component, "chlorophyll".

MED Principle 2: Highlight key events and processes in terms of energy. We wanted our mechanistic photosynthesis animation to help students track the flow of energy, where it is stored at the beginning and end of the process. To this end, we use a zoomed-in perspective of the chloroplast, namely to the level of inside the thylakoid stacks. This perspective depicts the biological setting for energy transfer and transformation during photosynthesis.

For the four key mechanistic moments, we sought to convey the transference of energy from a photon of light, through the chlorophyll, to hydrogen atoms, its transformation into chemical energy, and the storage of that energy in the glucose molecule. We designed the sequence to emphasize the interdependence of energy and matter during the photosynthesis process, specifically that energy is needed to transform matter, and that matter is needed to transform energy.

MED Principle 3: Guide towards causal-mechanistic relationships. To support students in recognizing the causal and mechanistic relationships in the animation were linked the animation segments associated with the four key moments events to form a cascading action sequence.

To support students' understanding of the principle of conservation of matter, we arranged the atoms and molecules in grids to facilitate counting and tracking (Figure 3). Furthermore, we wanted our animation to show the chemical reactions of photosynthesis as they occur within the biological constraints of a plant cell. Most chemical equations for photosynthesis show six water molecules as inputs, and none as outputs, the result of cancelling the six water molecules that are both inputs and outputs. We reasoned that by including the additional water molecules, students could understand the different roles that each atom plays (e.g., all the oxygen in glucose comes from the carbon dioxide; all the oxygen atoms from water are expelled as waste). We believe these details are critical for helping students understand photosynthesis in terms of the mechanisms associated with energy and matter transformations.

MED Principle 4 and 5: Present molecular interactions in terms of machine-like activities; Present molecular complexes as functional modules that are abstract, dynamic and transient in nature. To help middle school students understand the role of energy and the complex macromolecules in photosynthesis, we designed icons for them with visual analogies (Figure 2). For example, we used a basketball hoop as the icon for Photosystem II, to highlight its function to capture and direct light energy to an associated water molecule. We designed the icon for ATP Synthase to mimic a water wheel, because, structurally, ATP Synthase turns like a wheel as hydrogen ions flow through it, and, functionally, it harnesses the energy of the flowing hydrogen ions to create ATP from ADP. We depicted ATP and ADP as fully charged and minimally charged batteries, respectively, because ATP transports and transfers chemical energy throughout the plant cell to power energy-intensive processes. In a plant cell, a complex of enzymes in the Calvin Cycle make glucose from CO2 and hydrogen.

Design Testing

Pilot Test

Pilot Students. After viewing the animation, all six students accurately described the photosynthesis process. Specifically, they described how the energy from a photon of light was captured by the chlorophyll and used the split the water molecule. They noted how the oxygen atoms from water left the chloroplast as oxygen gas and the remaining hydrogen atoms went on to power the movement of the apparatus. They further described how the movement of the apparatus charged

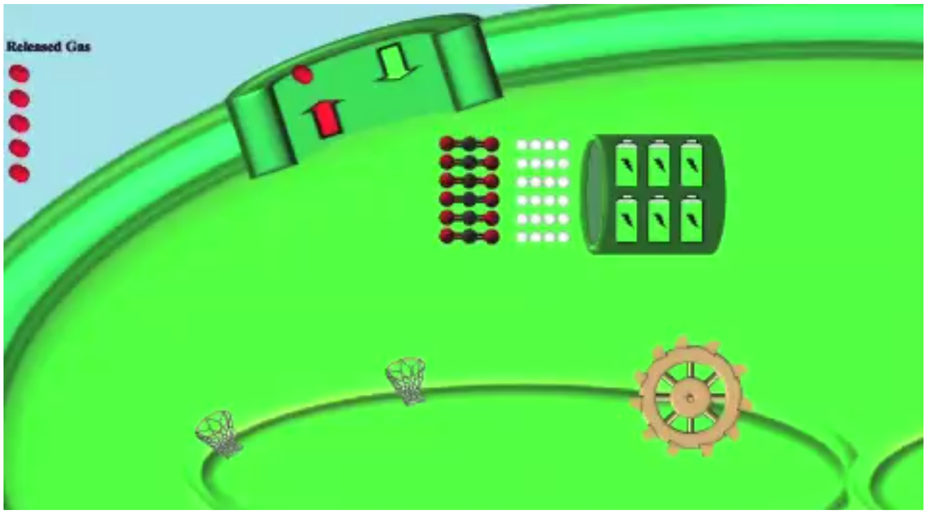


Figure 3: Screenshot of Mechanistic Photosynthesis Animation right before glucose is produced. 6 molecules of carbon dioxide and 24 atoms of hydrogen are about to enter the glucose machine. The full batteries represent ATP, which provides the energy for this reaction. 5 molecules of oxygen gas have already left the chloroplast and are lined up at the left. A sixth molecule of oxygen gas is on its way to join them.

the energy molecule, which was then used in the formation of glucose from carbon dioxide and the hydrogen atoms. When asked for comments on the animation's clarity, students in our pilot test indicated that the analogy-based icons were helpful, especially the depiction of chlorophyll as a net that captures light energy. Students thought some aspects of the animation were inaccurate: they thought all the atoms in carbon dioxide should break apart before forming glucose. This common student idea that inputs break down completely (Zhang & Linn, 2011) is not consistent with many chemical reactions, including glucose formation. In the test version of our animation, glucose formed as a result of the convergence of carbon dioxide molecules, hydrogen atoms, and ATP molecules (charged batteries) to a single location. Understanding that glucose formation is complex and takes many steps, one student recommended that the inputs go into something, then emerge as the outputs.

Pilot Teacher. Our pilot science teacher appreciated the detailed depiction of the primary chemical reactions of photosynthesis (e.g. light-mediated splitting of water and quantifiable atomic inputs during glucose production), especially since her class had just completed a unit on chemical reactions. She also liked how energy was depicted as a process mediator (e.g., with energetic hydrogen atoms moving to and turning the energy wheel) rather than as an object, which she noted is a common depiction of energy in middle school science resources. She commented that she thought the water wheel icon representing ATP Synthase would help her achieve the goal of getting her students to understand energy as a process mediator rather than entity. However, she suggested that we slow down the speed at which the wheel icon turned so that students could more easily recognize and understand the energy transfer process, namely that the motion of the hydrogen leads to the turning of the wheel, which leads to the charging of the energy carrier. support students Overall, this teacher approved of using analogy-based icons to depict complex molecular structures and functions.

Field Test

Field Students. During the field test, the students worked in teacher-assigned pairs to complete the online science inquiry unit. This structure allowed the students to collaboratively view and develop an understanding of the information presented in the animation. All students seemed to be seriously engaged with the animation as evidenced by their focused viewing and reviewing of the animation using the playback controls. Regarding specific feedback, two students commented that the animation could be improved by adding narration or captions. One student suggested having a narrated portion at the beginning of the animation to provide an explanation of each icon. Other students suggested re-positioning the legend to the side rather than top of the animation so that they could reference the legend while viewing the animation. One student pair suggested the use of zooming or panning in to follow the action as a way to help them focus on the most important aspects at each point in the animation.

Overall, students commented that the animation was clear and understandable. When asked whether the animation made sense, rather than a simple "Yes", one student spontaneously offered the following: *"This shows that you have the yellow [uncharged] battery, and it needs to be charged. These (pointing to the water molecule) hydrogen and oxygen come in and the light energy comes. And they [the uncharged batteries] use the hydrogen. And later after all of these (pointing to the array of each of the six carbon dioxide molecules lined up four hydrogen atoms) have gotten paired...it'll [the array of carbon dioxide and hydrogen] push through and it'll [the glucose machine] decharge all the batteries, because it took energy to make glucose."*

Field Teacher. During the classroom observation, the teacher commented on how impressed she was by the level of sophistication with which her students were discussing photosynthesis while engaging the animation. She noted that she has taught photosynthesis for a while but has never heard her students discussing the topic at such a high level of sophistication.

During the informal interview the teacher expressed appreciation for the way the animation focused on the flow and function of energy during photosynthesis. She stated that this was a stark contrast to all the other curriculum content she encountered, having taught at all levels from 5th grade to higher education. She commented, *"It only focused on matter, and they didn't really understand the energy at all. So this is really great, how it's actual discussion on the energy, because they didn't really get it. The stuff that was out there for middle school just didn't focus on that."* She also expressed her opinion, as a graduate-level trained molecular biologist, that not having a solid energy understanding prevents students from developing a robust understanding of photosynthesis and other science phenomena. She commented, *"The matter doesn't really matter as much, because the whole point of photosynthesis is to capture energy and store it. So, the fact that they are seeing with your [animation] where the energy is going, how it's been transformed and transferred, is great."*

Animation Redesign

In response to the pilot test comments from students we modified the potentially misleading depiction of glucose synthesis resulting from a convergence of carbon dioxide and hydrogen and tested it in the field test. Specifically, we redesigned the animation to include an icon that we called the glucose machine. Rather than having the molecules and atoms converge, the glucose machine took as inputs six CO2 molecules and 12 hydrogen atoms and outputted one glucose molecule. The glucose machine thus represented the network of complex chemical reactions in the Calvin Cycle, an aspect of the process that was previously excluded to maintain middle school-level accessibility. By including the Calvin Cycle as a visible "black box", we created an opportunity for further exploration without compromising accessibility. This redesign to include the glucose machine was valuable for the students in the field test.

In response to the field test students, we focused on instructional scaffolds. We did not redesign the animation to include a narration or captions as suggested by the field test students, although this suggestion aligns with the multimedia design principle put forth by Mayer and Moreno (Mayer & Moreno, 2003). Instead, we focused our efforts on instructional scaffolds outside the animation following the Quintana et al. (2004) design principles. We resolved the legend position issue by modifying a technical setting to allow automatic resizing so that the animation and legend would fit on the screen together without scrolling.

Based on field notes, to help students focus on the most important aspects at each point in the animation we restructured the animation to make the four key moments distinct segments of the animation (consistent with AD Principle 2). This was done by redesigning the animation to be interactive and have action checkpoints that must be satisfied in order for the animation to proceed. Redesigns will be field tested in future studies.

Discussion

To make mechanistic explanations of photosynthesis visible and available for analysis by middle school students, we designed and tested an animation and supporting activities. We developed a molecular-level depiction of the mechanism of photosynthesis using a combination of cartoon-like and analogical icons of the relevant atoms, molecules, and macromolecules. Employing a DBR methodology in conjunction with both animation and molecular-level explanation design principles, we designed a mechanistic photosynthesis animation that 1) targets complex ideas of energy transfer and matter cycling, 2) depicts the mechanism of energy and matter transformation, and 3) requires minimal (6th-grade) science knowledge to understand. Feedback from our chemistry partners helped us to accurately depict the role of energy and matter transformation during the chemical reactions that occur in photosynthesis, while our 8th-grade student partners helped us ensure that the animation was appropriate for middle school. The result of this guidance helped us support 6th grade students to develop a nuanced understanding of glucose synthesis. From the animation they were able to describe how energy from light rather than directly being stored in glucose is transferred via hydrogen atoms to charge energy carrier molecules which provide the requisite energy to make glucose using carbon dioxide and hydrogen. Our teacher partners gave us additional reassurance that the animation could function as a valuable curricular resource to help students develop a robust understanding of both energy and matter in photosynthesis, and thus meet the middle school life science NGSS photosynthesis standard.

The resulting animation enabled students in the pilot and field trial to produce a mechanistic explanation and deepen their understanding of photosynthesis. These results suggest that, with instructional materials designed according to research-based principles, middle school students could benefit from mechanistic explanations of photosynthesis.

New Animation Design Principles

The design principles used in this study provided strong but incomplete guidance to meet our goal of designing an animation to support students in developing a mechanistic understanding of how photosynthesis facilitates the cycling of matter and flow of energy. While the design principles supported us in determining how to present the animation content, we realized the need for guidance in determining what to present. Fortunately, our methodological choice of DBR allowed us to meet this need by drawing upon the expertise of our content experts and partner teacher and students. However, to guide future design efforts for science-related software tool, we offer an additional scaffolding design principle for the sense-making element of science inquiry: *Include conceptual content deemed foundational by discipline experts.*

Focusing on conceptual content rather than precise content creates greater freedom in determining the level of detail to include for a given target audience. For example, in this study the chemistry expert on our design team highlight the integral nature of ATP synthase in understanding how photosynthesis facilitates the transfer and flow of energy. By combining their recommendation on what to include (i.e. the function of ATP synthase) with our design principle of how to present it (i.e. use representations and language that bridge learners' understanding), our animation would likely have fallen into the same category as previously existing animations, either too complex or too superficial. Using our new scaffolding design principle in conjunction with the others used in this study, can provide developers with guidance for how to negotiate NGSS boundary assessments and support students to fully meet the learning goals of the NGSS and other ambitious science education efforts.

Study 1 Conclusions

The mechanistic photosynthesis animation met our design goals and incorporated results from the pilot and field trial. The next step is to test the animation in classrooms to determine how it supports students to 1) develop a robust and coherent understanding of the mechanism of energy and matter transformation during photosynthesis, and 2) meet the NGSS performance expectation to construct a scientific explanation based on evidence for the role of photosynthesis in the cycling of matter and flow of energy into and out of organisms. These issues are addressed in Study 2.

STUDY 2 - MECHANISTIC PHOTOSYNTHESIS ANIMATION CLASSROOM EVALUATION

Introduction

Current middle school science curricula reflect a conventional belief that 7th grade students are not cognitively ready for instruction on the mechanisms that undergird natural phenomena (National Research Council, 2012). We assert that excluding an exploration of mechanisms from the study of natural phenomena, such as photosynthesis, misses an opportunity to support middle school students in developing the integrated scientific knowledge called for by the Next Generation Science Standards (NGSS; National Research Council, 2012). Our review of currently available photosynthesis animations that are targeted for middle school instruction revealed a critical need to develop animations suitable for students at this level of education. Therefore, we designed and field tested our Mechanistic Photosynthesis Animation that demonstrated an ability to support 7th grade science students in understanding the biochemical mechanism of photosynthesis as it relates to energy and matter transformation (ref. Study 1).

In this study, we extended the evaluation of our Mechanistic Photosynthesis Animation by conducting a classroom study consisting of 205 students taught by two 7th grade science teachers. We embedded the Mechanistic Photosynthesis Animation in an inquiry science unit on photosynthesis and cellular respiration in the Web-based Inquiry Science Environment (WISE; Slotta Linn, 2009) to scaffold students' engagement and learning with the animation. We developed unit-based instruction and assessments according to research-based design principles (Quintana et al., 2004; Millar et al., 2005; van Mil et al., 2013; van MIL et al., 2016) and the Knowledge Integration (KI) framework (Linn et al., 2011).

A previous study by Ryoo and Linn (2012), which utilized an animation and guiding questions developed using the KI framework, showed that middle school students can understand photosynthesis as a chemical process involving matter transformation (i.e. carbon dioxide and water transforming into glucose) and energy transformation (i.e. light energy transforming into chemical energy). The instruction in that study encouraged students to generate their own explanations to connect photosynthesis to concepts like conservation of matter and energy (Ryoo & Linn, 2012). While these efforts led to increased learning gains from pretest to post-test, reflected in students' ability to express that light energy initiates the process of matter transformation, these gains did not include the development of a mechanistic understanding of how energy is used and changed throughout photosynthesis, a critical aspect of the NGSS performance expectations for this phenomenon.

In this paper, we address the research questions of whether our previously design Mechanistic Photosynthesis Animation can support students to: (a) develop a robust and coherent understanding of the mechanism of (i.e. how) energy and matter transformation during photosynthesis, and (b) construct a scientific explanation based on evidence for the role of photosynthesis in the cycling of matter and flow of energy into and out of organisms (i.e. matter and energy transformation). We argue that the Mechanistic Photosynthesis Animation and associated instructional scaffolds supported over 60% of the students to use a mechanistic explanation to describe how energy and matter transform during photosynthesis. We contend that by developing an animation according to research-based design principles for teaching energy and for supporting integrated knowledge, multimedia learning, and molecular-level explanations, we were able to extend the current curriculum boundaries and effectively support middle school students to understand complex scientific concepts typically taught in high school. This study provides insight for how to develop curriculum resources that help students meet the ambitious goals set forth by NGSS and other reform-based science standards.

Rationale

While energy and matter are crosscutting concepts that relate to many science topics, in this study, we focus on photosynthesis. Photosynthesis is a featured topic in the NGSS middle school standards and is familiar to middle school teachers and students, given its longstanding presence in primary and middle school curricula. Prior to NGSS, standards for middle school science emphasized superficial aspects of photosynthesis (Kesidou & Roseman, 2002; Roseman et al., 2010). For example, the 2000 California standards for middle school science (Ong et al., 2000) focused on the names of the inputs and outputs (e.g. light, water, glucose, etc.), the cellular location of the process (i.e the chloroplast), and its overall purpose (i.e. to store energy for the plant). This type of instruction not only de-prioritizes an understanding of how photosynthesis occurs, it also allows students to maintain a naive assumption about the photosynthesis reaction: that light (perhaps in combination with carbon dioxide and water) becomes glucose (Ryoo & Linn, 2014; Keleş & Kefeli, 2010; Marmaroti & Galanopoulou, 2006). When we asked, on our study's pre-test, how a rabbit gets energy from the sun, a 7th grader responded,

> "In plants, these energy factories are called chloroplasts. They collect energy from the sun and use carbon dioxide and water in the process called photosynthesis to produce sugars. Animals can make use of the sugars provided by the plants in their own cellular energy factories, the mitochondria."

The above student response would have met the Life Science Standards for California (Ong et al., 2000) and most other states' science standards in 2000. This response indicates that the student knows that "energy entering ecosystems as sunlight is transferred by producers into chemical energy through photosynthesis" (6th grade life science standard) and that "mitochondria liberate energy for the work that cells do and that chloroplasts capture sunlight energy for photosynthesis" (7th grade life science standard). Similar to this example, Abrams and Southerland (2001) observed that students have difficulty explaining how natural phenomena occur. They, like Anderson et. al (1990), attribute this difficulty in part to the prioritization in curricula of explaining the role or purpose of the phenomena - the why rather than the how.

However, curriculum standards are changing. In fact, this response falls short of meeting the new middle school life science standard in the Next Generation Science Standards (NGSS), for which the student's response would additionally need to highlight the cycling of matter and the flow of energy. Specifically, they would need to describe photosynthesis and cellular respiration as processes consisting of a series of chemical reactions that require an input of energy to rearrange the input molecules (i.e. carbon dioxide and water) into the output molecules (i.e. glucose and oxygen). They would also need to describe how energy is transferred and transformed during these processes (NGSS, MS-LS1-6, MS-LS1-7). To illustrate, we examine the following response generated by one of our 7th-grade study participants at post-test:

> “The rabbit gets it’s [sic] energy from the plants it eats. These plants get there [sic] energy from a process called photosynthesis were [sic] they make their food glucose. Photosynthesis is were [sic] six carbon atoms enter through the cell wall of a plant. Then two water atoms enter and are broken down by the light energy (photon). The oxygen from the water molecules leave but the four hydrogen molecules are used to charge an energy carrier. The energy carrier goes on the energy machine and the hydrogen line up next to the carbon dixode [sic]. This process is repeated six times before the glucose is made. Once there are 24 hydrogen and six CO2 molecules the molecules go through the energy machine and take energy from the energy carriers. On the other side they form a glucose molecule...”

Compared to the previous response, this response delineates the path and ultimate fate of the matter and energy that the plant takes in for photosynthesis. Specifically, the student makes clear that the light energy is used to split the water into hydrogen and oxygen, with the latter leaving the plant cell and the former continuing on to facilitate the transfer and transformation of energy from light to the energy carriers (i.e. ATP). The student continues to track the input energy by describing how it is used to rearrange the carbon dioxide molecules and hydrogen atoms into the final product, glucose. This response shows that photosynthesis includes several steps, each of which involves some transformation or transfer of energy or matter. By attending to the path of the matter and energy during the photosynthesis process, this student was able to construct a scientific explanation of how a rabbit gets energy from the sun and thereby meet the NGSS performance expectation associated with photosynthesis.

Moreover, the NGSS middle school life science performance expectation calls for students to construct scientific explanations of how photosynthesis facilitates the cycling of matter and the flow of energy (NGSS, MS-LS1-6):

> Construct a scientific explanation based on evidence for the role of photosynthesis in the cycling of matter and flow of energy into and out of organisms. [Clarification Statement: Emphasis is on tracing movement of matter and flow of energy.] [Assessment Boundary: Assessment does not include the biochemical mechanisms of photosynthesis.]

The National Research Council framework document for the NGSS provides insight into the committee’s definition of scientific explanation:

> “Scientific explanations are accounts that link scientific theory with specific observations or phenomena—for example, they explain observed relationships between variables and describe the mechanisms that support cause and effect inferences about them.” (National Academies Press, 2012, p. 67).

This definition of scientific explanation incorporates mechanistic reasoning, which science education researchers argue is critical for developing an integrated and robust understanding of natural phenomena (Abrams & Southerland, 2001; Russ et al., 2008; Krist et al., 2018). Indeed, the clarification statement for the photosynthesis standard encourages instruction that allows students to trace the movement of matter and flow of energy. Taken together, it follows that the ideal instruction would include exploration of the mechanism of photosynthesis. However, for most states, the mechanistic details of energy and matter transformation during photosynthesis are not included in instruction until high school.

The rationale for excluding these mechanistic details from middle school instruction seems to lie in the belief that middle school students are not cognitively ready to understand, at a mechanistic level, the complexities of science concepts like energy and matter transformation (National Research Council, 1996). Ironically, this ideology manifests in the NGSS boundary assessment for the photosynthesis standard which discourages a mechanistic presentation of photosynthesis. According to the National Research Council framework document, the assessment boundaries "serve two purposes: (1) to delimit what level of detail is appropriate and (2) to indicate what knowledge related to a core idea may be too challenging for all students to master by the end of the grade band" (National Research Council, 2012). Although the NGSS assessment boundary clarifies that this standard does not require instruction of the biochemical mechanisms associated with photosynthesis, leaving out those mechanisms will likely perpetuate the difficulty that students have with explaining how natural phenomena occur and make them unable to construct a scientific explanation that would meet the definition provided in the framework document. This point is illustrated by a sample response from the Ryoo and Linn (2012) study:

> "The chlorophyll in the chloroplasts of the plant captures the Sun's light energy. The light energy is used to break up the molecules of carbon dioxide and water that the plant absorbs into smaller molecules. Without the broken molecules, the plant could not make glucose, so the plant needs light to survive. In another part of the chloroplast, the broken-up molecules are chemically combined to create a sugar called glucose and oxygen, which the plant gets rid of. This chemical combining is called photosynthesis. The plant uses most of the glucose in its cellular processes, but it stores some of it for later use. When a rabbit eats the plant, it absorbs the stored glucose and uses it in its cellular processes. This occurs over and over again, so that every organism gets its energy from the Sun." (p. 236).

Although the animation in the Ryoo and Linn (2012) study provided a molecular-level depiction of photosynthesis it did not depict the mechanism by which energy and matter transform. We argue that omissions such as these contribute to students' inability to explain how energy is involved in both the breakdown and formation of matter and how matter is involved in the transformation of energy. Our conjecture in the research presented here is that engaging students in instruction that includes a mechanistic presentation of photosynthesis focused on energy and matter transformation will support them in developing a robust understanding of the phenomenon and allow them to construct a scientific explanation of how photosynthesis facilitates the cycling of matter and flow of energy in and out of organisms. We base this conjecture on numerous studies that demonstrate the ability of young children to engage in mechanistic reasoning (Grotzer, 2003; Russ et al., 2008; Krist et al., 2018). Given the current lack of curricular resources that support students in developing an integrated and mechanistic understanding of how energy and matter transform during photosynthesis (Kesidou & Roseman, 2002; Roseman et al., 2010; Abrams &

Southerland, 2001) and the increase in state adoption of the NGSS, we recognize the need to develop NGSS-aligned curriculum resources to better support students in developing this type of understanding.

In this paper, we report the design of a mechanistic animation of photosynthesis that focuses on energy and matter transformation and instructional scaffolds that supports students' learning from the animation. We further report that, after learning from the animation, students in our study incorporated the mechanism of photosynthesis into their post-test explanation of how a rabbit gets energy from the sun, as illustrated in the above sample response. Below, we describe the animation design features and associated instructional supports that helped the 7th-grader who wrote the post-test response presented above to develop such a sophisticated understanding of this complex phenomenon.

Research Questions

With prior instruction primarily supporting students to understand the why of photosynthesis, the question remains, can middle school students develop a robust and coherent understanding of how energy and matter transform during photosynthesis? To address this question, we conducted a classroom study to assess student learning from the Mechanistic Photosynthesis Animation and specifically asked:

Does productive engagement with the animation and structured instructional scaffolds support students to:

- develop a robust and coherent understanding of the mechanism of (i.e. how) energy and matter transformation during photosynthesis?
- construct a scientific explanation based on evidence for the role of photosynthesis in the cycling of matter and flow of energy into and out of organisms (i.e. matter and energy transformation)?

Design Principles

To develop the mechanistic photosynthesis animation used in this study (manuscript under review), we drew upon several frameworks and principles: Knowledge Integration (KI) framework (Linn et al., 2011), multimedia learning design principles (Mayer & Moreno, 2003), design principles for teaching energy (Millar et al., 2005), design principles for molecular-level explanations (van Mil et al., 2013; van MIL et al., 2016) and a scaffolding design framework (Quintana et al., 2004). We synthesized and grouped these principles into two categories, animation design principles and molecular-level explanation design principles. While the animation design principles guided the design of the non-science aspects of our mechanistic photosynthesis animation (e.g., play-back controls, use of text, graphic design, etc.), the molecular-level explanation design principles guided the science-aspects of the animation and is the focus of this study.

To design the instructional unit for the mechanistic photosynthesis animation, we drew upon research-based theories about learning and instruction (Höffler & Leutner, 2007). Specifically, we used the KI framework for science instruction and scaffolding design principles for software tools (Quintana et al., 2004).

KI pedagogical framework

There is well-established research demonstrating the power of curriculum based on the Knowledge Integration framework to promote robust and coherent student learning ability, as measured by the integration of complex, normative science ideas (Vitale et al., 2016; Visintainer & Linn, 2015; Lee & Liu, 2009). Given our goal of supporting students to develop a robust and coherent understanding of the energy and matter transformations in photosynthesis, we used this framework to guide the design of the online inquiry science unit in which we embedded the mechanistic photosynthesis animation.

The KI framework provides guidance for supporting students to develop integrated science knowledge. It proposes that robust student learning results from making connections between ideas and calls for instruction that elicits and develops students' ideas through activities that promote idea evaluation and revision (Linn et al., 2011; D. Clark & Linn, 2013). The KI framework holds that students enter any learning environment with preformed ideas that were developed through interactions with their physical and social environments and that inform their understanding of new ideas (Linn et al., 2003). In KI-based instruction, students' ideas are elishortcited and made available for exploration and further development. Once elishortcited, students engage with models, simulations, and experimentation to add normative science ideas, and are provided with opportunities to distinguish amongst their prior and new ideas. This distinguishing step is critical for students to develop integrated knowledge as it is when students determine which ideas are most productive for understanding the phenomena under study. To engage students in the final step of the KI process, reflection, students are encouraged to synthesize their new understanding to generate a learning artifact.

Scaffolding design framework

To develop the instructional scaffolds to support student learning with the Mechanistic Photosynthesis Animation that we embedded in the photosynthesis unit, we utilized the scaffolding design framework developed by Quintana and colleagues (2004). The scaffolding design framework is a synthesis of theoretical research in learning and empirical research on technology-enhanced science inquiry learning and offers guidelines and strategies for designing software tools that address the learning needs and obstacles that students have when engaging in science inquiry instruction. The framework organizes the guidelines according to three science inquiry processes: sense making, process management, and articulation and reflection. In the following sections, we describe the learning needs, obstacles and guidelines associated with each of these inquiry processes as it relates to our study aims.

Sense making. Sense making in science is the process of moving from reasoning-based hypothesis to evidence-based explanation (Quintana et al., 2004; Schwarz et al., 2016). In terms of understanding the phenomenon of photosynthesis, middle school students' hypotheses are derived, in part, from ideas that they gain through prior schooling and personal experiences. The outcome of students' attempt to make sense of photosynthesis, as with many other science ideas, tends to be a collection of fragmented, contradictory, or non-normative ideas (D. Clark & Linn, 2013). For example, students know from personal experience that plants grow when they are exposed to sunlight, and, when they learn in school that plants use sunlight during photosynthesis to make sugar (i.e. glucose), they often reason that photosynthesis is the process plants use to, literally, convert sunlight into glucose (Jin & Anderson, 2012; Ryoo & Linn, 2014). Although reasonable, this idea is inconsistent with scientific understanding, and Reif Larkin (1991) contend that it stems from the disconnect between scientific thinking and students' everyday thinking. Developing a scientific understanding requires the ability to discriminate between the relevant and irrelevant aspects of a phenomenon. However, having such discernment requires substantial conceptual and domain-specific knowledge, which students likely do not yet possess (Hmelo-Silver & Pfeffer, 2004).

Quintana et al. (2004) argue that to engage in sense making that leads to the development of scientific knowledge, students need epistemic resources, like scientific representations and practices. This viewpoint is also reflected in the National Research Council's framework for K-12 science education, which calls for instruction that supports students to develop competence with disciplinary core ideas and crosscutting concepts, which are encoded in scientific representations, and science and engineering practices (National Research Council, 2012).

The online photosynthesis inquiry unit used in this study supports students in the sense making process by implementing the following scaffolding guidelines (Quintana et al., 2004):

Sense-making (SM) Guidelines

- Use representations and language that bridge students' understanding
- Organize tools and artifacts around the semantics of the discipline
- Use representations that students can inspect in different ways to reveal important properties of underlying data

Process management. To negotiate the transition from everyday thinking to scientific thinking, students need to employ productive strategies for sense-making. These strategies take the form of scientific practices, such as using models to develop and evaluate hypotheses and analyzing data (National Research Council, 2012). While scientists use these practices to navigate the inquiry process, these practices may be just as unfamiliar to students as the details of the phenomenon being explored (Sandoval, 2005). For example, students often explore data to confirm rather than evaluate their ideas (de Jong, 2019). In the case of photosynthesis, many students use the observational data that plants die without sunlight to confirm their prior idea that sunlight is food for plants (Keleş & Kefeli, 2010).

In this study, the Mechanistic Photosynthesis Animation models the photosynthesis process. To support students in using this model to explore and evaluate their hypotheses about how energy and matter transform during photosynthesis, we implemented the following scaffolding guidelines for process management (Quintana et al., 2004):

Process Management (PM) Guidelines

- Provide structure for complex tasks and functionality
- Embed expert guidance about scientific practices
- Automatically handle non-salient, routine tasks

Articulation and reflection. To solidify their understanding of complex natural phenomena, students need opportunities to articulate their developing ideas and reflect on their new understanding in contrast to their prior understanding (Tansomboon et al., 2017). Generating explanations is an effective means of developing integrated knowledge of complex science concepts as it makes students' ideas visible for inspection by themselves and others (Ryoo & Linn, 2014; Linn et al., 2011). Furthermore, the practice of revision supports students in reflecting on the information they are learning as compared to their starting knowledge (de Jong, 2019). When reflection is supported in the context of collaborative learning, students are able to evaluate and refine their ideas to develop more integrated knowledge (?, ?). Therefore, in this classroom study, we implemented the following scaffolding guideline (Quintana et al., 2004)

Articulation and Reflection (AR) Guideline

- Facilitate ongoing articulation and reflection during the investigation

Methods

In this section, we describe the study details as well as the specific strategy that we used to implement each of the seven previously listed scaffolding guidelines.

Participants

Two seventh-grade science teachers at a local, public middle school (18% English-language learners, 15% free/reduced price meals) participated in this study, along with their 205 students across a total of 7 class periods. One of the teachers was on the design team for the Mechanistic Photosynthesis Animation (ref. Study 1).

Study Activities, Materials, and Embedded Assessments

All of the students included in this study interacted with the photosynthesis animation and the study activities, which consisted of a pre-test, post-test, and embedded instruction and assessments.

Pre- and Post-test Assessments. There were two items on the pre- and post-test that assessed students' understanding of energy and matter transformations during photosynthesis. The first item assessed students' understanding of the inputs and outputs of photosynthesis, representing the basic elements of knowledge targeted by the instruction. Specifically, the pre- and post-test asked students to identify the inputs and then the outputs of photosynthesis from this list of options: carbon dioxide, water, light, oxygen, and glucose (Table 2). Students were scored correct for inputs if they selected only light, water, and carbon dioxide. Students were scored correct for outputs if they selected glucose and oxygen and did not select light or carbon dioxide (we accepted either choice for water since the animation portrayed it as an output, but the standard equation did not). We combined these two scores to create an overall Input-Output score for a total of three measures.

Individual students demonstrated their understanding of energy and matter transformation in their responses to the Energy Story pre- and post-test item (Table 2).

Unit-Embedded Assessments. The study instruction started with a presentation of the full Mechanistic Photosynthesis Animation (SM-1: accessible representations/language) and an open-response question (referred to as "Initial Explanation", Table 2). After writing their Initial Explanation, students were prompted to watch four video clips taken from the animation, which highlighted the key mechanistic moments of energy and matter transformation during photosynthesis and answer the guiding question associated with each clip (Figure 4; PM-1: structure for complex tasks).

Table 2: The prompts for each assessment item and the percentage of students who completed them.

Item	Prompt	% of Students who Completed
Photosynthesis Inputs (pre-/posttest)	What are the inputs for photosynthesis? Choose all correct answers: ❑ Carbon Dioxide (CO2) ❑ Water (H2O) ❑ Light Energy (Photon) ❑ Oxygen Gas (O2) ❑ Glucose	Pretest - 98.5% Posttest - 91.2%
Photosynthesis Outputs (pre-/posttest)	What are the outputs for photosynthesis? Choose all correct answers: ❑ Carbon Dioxide (CO2) ❑ Water (H2O) ❑ Light Energy (Photon) ❑ Oxygen Gas (O2) ❑ Glucose	Pretest - 98.5 % Posttest - 91.2 %
Energy Story (pre-/posttest)	A new student, Mary, comes to our class. There is a rabbit in the classroom. Mary wonders how the rabbit gets and uses energy from the sun. Write a story using scientific evidence to explain to Mary how the rabbit gets energy from the sun. Make sure you story explains: • Where energy comes from • How energy moves • Where energy goes • How energy changes/transforms	Pretest - 77.1 % Posttest - 90.2 %
Initial Explanation (embedded assessment)	Photosynthesis transforms light energy (from photons) into chemical energy (stored in glucose). What does this video show about the flow of energy through the photosynthesis process?	96.1 %
Final Explanation (embedded assessment)	Now that you've thought about it more, revise your answer. Photosynthesis transforms light energy (from photons) into chemical energy (stored in glucose). What does this video show about the flow of energy through the photosynthesis process?	91.2 %

To support students in developing a robust understanding of these complex chemical processes, we refined our guiding questions to draw upon what van Mil et al. (2016) termed the "general mechanistic reasoning structure". The general mechanistic reasoning structure encourages students to search for relationships between process agents and events as well as casual connections. Therefore, we designed the guiding questions for each clip to help students think about tracking energy through the animation, attend to the relationships between agents and events, and identify causal connections (SM-2: disciplinary semantics). We also included playback and navigation controls for the full animation and video clips such that workgroups could watch any portion of the animation or clips as much as they wanted (SM-3: differential exploration).

Finally, students were shown the full animation again and presented with a prompt to revise (PM-2: guidance for science practices). The initial prompt (above) was repeated and their Initial Explanation was automatically imported to the open response area to facilitate revision (PM-3: automatic non-salient tasks). We refer to their response to the revision prompt as Reflection Explanation. The Initial/Reflection Explanation and guiding questions for the video clips supported students in articulating and reflecting on their developing ideas throughout the investigation and represented our strategy for implementing the scaffolding guideline for these processes (AR-1: ongoing articulation/reflection). To determine the impact of the animation and the instructional scaffolds, we developed a unit-level pre- and post-test to assess students' understanding of energy and matter transformation during photosynthesis.

Classroom Use

The study instruction was embedded in a Web-based Inquiry Science Environment (WISE) unit on photosynthesis (`https://wise.berkeley.edu/project/19535`. One to three days prior to starting the unit, students individually took the pretest, which included assessment items on energy and matter transformation in photosynthesis that aligned with the study goals. Students accessed the unit with school-provided computers and worked in teacher-assigned groups of 2-3 students, although some students worked individually due to an absent partner (83 total workgroups). In sections preceding the study instruction, students learned about and responded to a non-scored, embedded item regarding the inputs and outputs of photosynthesis (Figure 5). However, the study instruction was the only portion of the unit that related to the mechanisms of photosynthesis. The remainder of the unit focused on cellular respiration and plant growth.

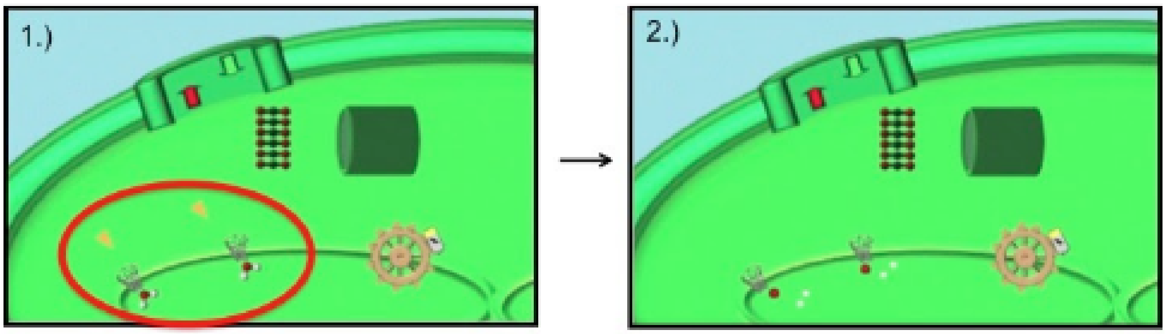
Study Conditions. Workgroups were randomly assigned by the WISE system to study conditions, Open-Response or Multiple-Choice, based on the format of the guiding questions for the four clips (Figure 4). Workgroups in both conditions were prompted with identical Initial/Reflection Explanation items. However, students in the Multiple-Choice condition (N=73) were provided brief explanations of the energy/matter transformation events depicted in the clips. The event explanations were located directly above the guiding question, which was formatted as a multiple-choice item. The decoy answer choices were worded to align with a superficial interpretation of the events based on visual cues (e.g. the energy disappeared in the reaction). Students in the Open-Response condition (N=64) were prompted with the same guiding questions as students in the Multiple-Choice condition, however, they had to construct their own explanations of the depicted events.

These conditions were chosen to evaluate two reasonable approaches for supporting students in

Video Clip 1 - Disappearing Photons (2 secs)

Prompt: Photons are light energy. In the video, the photon disappeared. What happened to the energy?

Key Mechanistic Events: *Transfer of Energy from Photon + Splitting of water*



Action Summary: 1.) Two photons enter from the top left corner of the screen towards the two chlorophylls (basketball hoops), each of which having a water molecule associated with it. 2.) After capturing the photons, the chlorophylls (basketball hoops) vibrate, causing the water molecule to split into an oxygen atom (red dot) and two hydrogen atoms (white dots) and move to the energy apparatus (wheel).

Clip1 Multiple-Choice Prompt

Watch the photon in the clip below. The photon (light energy) hits the chlorophyll, transferring energy that makes the chlorophyll vibrate. The vibrations are so strong they break the water molecule into atoms. Photons are light energy. In the video, the photon disappeared. What happened to the energy?

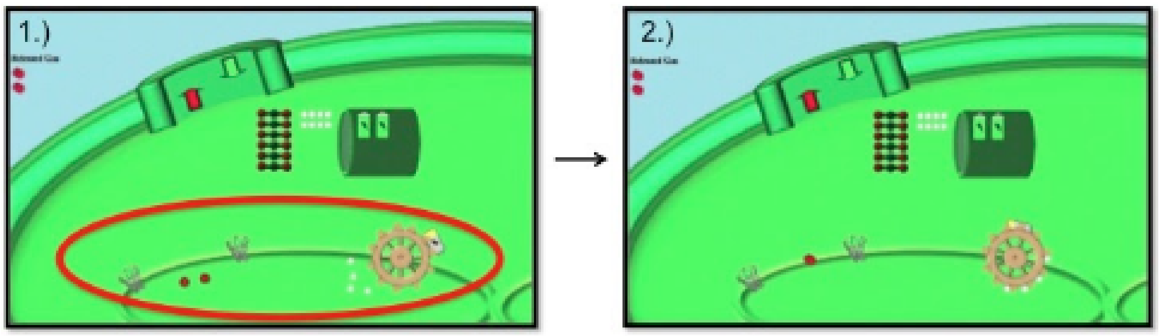
A. The energy disappeared with the photon, which means the energy is gone.
B. The energy made the chlorophyll vibrate, which separated the atoms in the water molecule.
C. The energy made the chlorophyll vibrate, which separated the atoms in the carbon dioxide molecule.

Clip 1 Open-Response Prompt

Watch the photon in the clip below. Photons are light energy. In the video, the photon disappeared. What happened to the energy?

Video Clip 2 - Hydrogen Turns the Energy Wheel (1 sec)
Prompt: Where did the energy wheel get the energy to turn?

Key Mechanistic Events: *Transformation of Kinetic Energy to Chemical Energy*

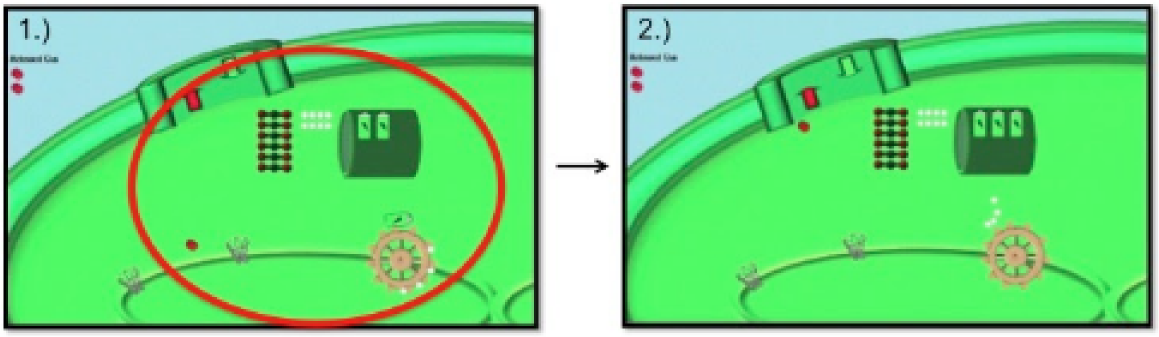


Action Summary: 1.) The oxygen atoms (red dots) move towards each other, and the hydrogen atoms (white dots) move towards the energy apparatus (wheel). 2.) The oxygen atoms (red dots) combine to form a single oxygen molecule. The hydrogen atoms (white dots) load onto the energy apparatus (wheel) that has an uncharged energy carrier molecule (yellow, partially filled battery) on it, which causes the energy apparatus (wheel) to turn.

Clip 2 Multiple-Choice Prompt	Clip 2 Open-Response Prompt
Watch the hydrogens in the clip below. The hydrogens are moving fast. They have a lot of movement energy. When the hydrogens hit the energy wheel, they transfer their energy to the energy wheel, making the wheel turn. Where did the energy wheel get the energy to turn? A. From the moving hydrogens. B. From the moving oxygens. C. From making its own energy.	Watch the hydrogens in the clip below. Where did the energy wheel get the energy to turn?

Video Clip 3 - Energy Wheel Charges Energy Carriers (3 secs)
Prompt: What happens to the movement energy from the energy wheel?

Key Mechanistic Event: *Transformation of Kinetic Energy to Chemical Energy*



Action Summary: 1.) The oxygen molecule (merged red dots) moves to the top of the screen to leave the chloroplast. Once fully turned, the energy apparatus (wheel) fully charges the energy carrier molecule (green, filled battery). 2.) The oxygen molecule (merged red dots) continues moving to the top of the screen to leave the chloroplast. The fully charged energy carrier molecule (green, filled battery) moves to the glucose reaction apparatus (green barrell). The hydrogen atoms (white dots) move to line up with the other hydrogen atoms to the left of the glucose reaction apparatus, which already has six carbon dioxide molecules lined up next to it.

Clip 3 Multiple-Choice Prompt

Watch the energy wheel in the clip below. The movement energy in the wheel is transformed into chemical energy to charge up the energy carrier molecule from low energy to high energy. After charging the energy carrier, the wheel has less energy and can't move. What happens to the movement energy from the energy wheel?

A. It is transformed into chemical energy to make the oxygen leave the chloroplast.
B. It disappears from the chloroplast when the wheel stops turning.
C. It is transformed into chemical energy to charge up the energy carrier.

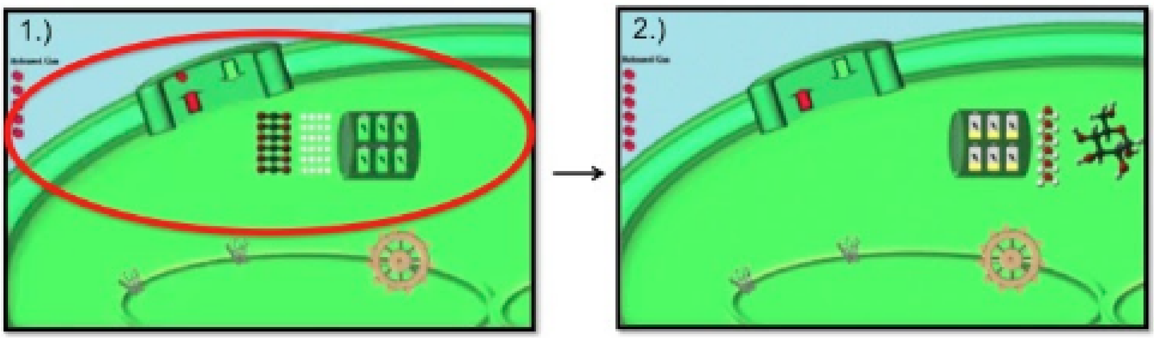
Clip 3 Open-Response Prompt

Watch the energy wheel in the clip below. What happens to the movement energy from the energy wheel?

Video Clip 4 - Making Glucose and Water (4 secs)

Prompt: After glucose is made, why are the energy carrier molecules low energy instead of high energy molecules?

Key Mechanistic Event: *Production of Glucose*



Action Summary: 1.) The oxygen molecule (merged red dots) moves towards the left of the screen to line up with the other released oxygen molecules outside the chloroplast. The 6 carbon dioxide molecules and 24 hydrogen atoms (white dots) lined up to the left of the glucose reaction apparatus (green barrell) move to the right to converge and disappear into the glucose reaction apparatus. 2.) The 6 fully charged energy carrier molecules (green, filled battery) loaded onto the glucose reaction apparatus get depleted and change into uncharged energy carrier molecules (yellow, partially filled battery). Six water molecules and one glucose molecule emerge from the right of the glucose reaction apparatus.

Clip 4 Multiple-Choice Prompt

Watch the molecules in the clip below. When all the needed molecules are there, they enter the glucose machine and are rearranged into glucose and water. This process transfers the energy from the energy carrier molecules to the new glucose molecule and the 6 water molecules. Glucose stores chemical energy. After glucose is made, why are the energy carrier molecules low energy instead of high energy molecules?

A. The energy disappeared in the reaction.
B. The energy was transferred to make glucose and water.
C. The energy was transferred to the chlorophyll.

Clip 4 Open-Response Prompt

Watch the molecules in the clip below. After glucose is made, why are the energy carrier molecules low energy instead of high energy molecules?

Figure 4: Description of the prompts and key concepts associated with the four Mechanistic Photosynthesis Animation video clips along with a visual and text-based summary of the action sequence depicted in each.

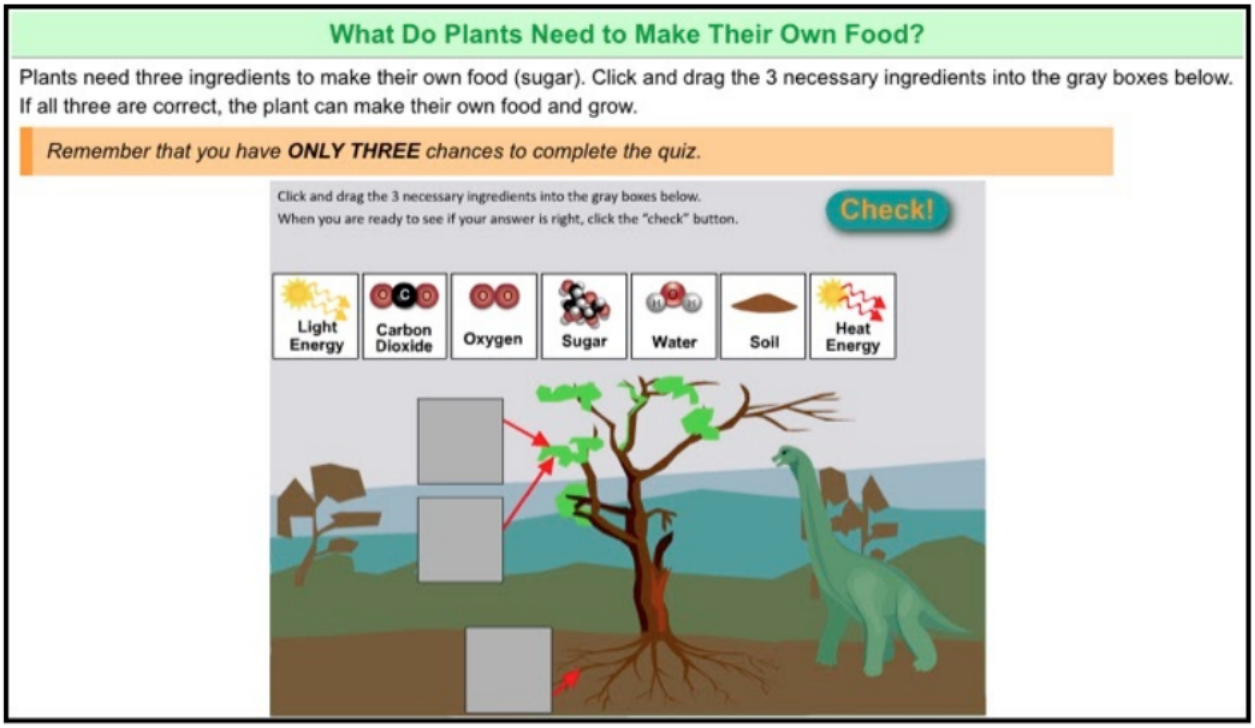


Figure 5: A screenshot of the interactive activity that students completed after learning about the inputs and outputs of photosynthesis but prior to engaging the study instruction. After placing the appropriate tiles from the horizontal line of options in the correct grayed out boxes, the dinosaur animates and the text to the left of the "Check!" changes to read, "Great job! Plants need light energy, carbon dioxide from the air, water to make their own food, a type of sugar. Let's go to the next step and explore how plants get these elements!"

the sense-making process. We designed the Multiple-Choice conditions to address the case where the complex events depicted in the Mechanistic Photosynthesis Animation overwhelms students and prevents them from generating their own explanations of the energy/matter transformation events (R. E. Clark & Feldon, 2014). We designed the Open-Response condition with the assumption that students would not be overwhelmed by the complexities and that generating their own explanations would support their sense-making of energy and matter transformation during photosynthesis, as demonstrated by Ryoo and Linn (2014). Analysis using Fisher's exact test demonstrated that there were no statistically significant differences in terms of relevant prior knowledge between the students assigned to each study condition (Inputs Only: $p = 0.375$; Outputs Only: $p = 0.865$; Inputs Outputs: $p = 0.259$) and how energy and matter transform during this process (Energy Story: $p = 0.999$).

Unit Progression. Teachers led their classes normally during the unit, including opening each period with topic reviews and class discussions. Teachers also evaluated students' work and provided written feedback using the WISE system regarding students' progress through the unit.

Specifically, Teacher 1 provided written feedback for 8 students (12%) and Teacher 2 provided written feedback for 28 students (39%). During our classroom observations, we also noticed that after reading through student responses Teacher 2 orally encouraged her students to give careful thought and attention to the photosynthesis animation and video clips as they responded to the associated embedded assessments. Although students progressed through the unit in groups, they individually completed the post-test 1-3 days after finishing the unit. On average, students completed the unit in seven days. The study instruction was embedded near the beginning of the unit, and most students completed the study instruction by the second day of the unit.

Data Sources

I conducted observations of each teacher's classes and took handwritten field notes to record students' behaviors as they engaged with the animation and unit instruction.

Additionally, we report results from the study instruction and the pre-to-post learning gains on the assessment items in the unit that aligned with the study goals (Table 2). Of the 205 students who participated in the study, 137 students (83 workgroups) submitted responses to all pre- and post-test items, and all unit-embedded assessments. These 137 students (83 workgroups) are included in the analysis below.

Energy-Matter Rubric

We developed a Knowledge Integration (KI) rubric to measure students' mechanistic reasoning and their understanding of the interdependence of energy and matter during photosynthesis. KI rubrics prioritize linked normative ideas with higher scores corresponding to more coherent understanding of a scientific phenomenon based on relevant scientific ideas rather than fragmented or non-normative ideas (Liu et al., 2011). The approach used to develop a KI rubric has been shown to generate levels on the knowledge integration construct that are distinctive, valid, and reliable (Liu et al., 2008). Given the focus of NGSS and other science reform efforts on the development of coherent, integrated science knowledge (e.g. three-dimensional learning), we identified the KI rubric as a key tool for assessing students' understanding of how energy and matter transform during photosynthesis (i.e. Initial and Reflection Explanation responses) as well as its role in the cycling of matter and flow of energy (i.e. Energy Story responses). Furthermore, since integrated knowledge is the construct that a KI rubric measures, it might also be a good tool for measuring students' ability to construct a scientific explanation (ref. NGSS, MS-LS1-6), which requires that students "explain observed relationships between variables and describe the mechanisms that support cause and effect inferences about them" (National Research Council, 2012, p. 67).

To exhibit mechanistic reasoning, responses needed to describe the relationship between process agents and events and establish causal links. To exhibit an understanding of process interdependence, responses needed to describe the relationship between energy and matter during the transformation process (i.e. the role of energy in matter transformations, and the role of matter in energy transformations). We used this revised KI-based rubric to score students' pre-/post-test and embedded open-response essays.

Table 3: Energy-Matter Rubric and Sample Responses Rubric used to assess students' responses to the embedded assessments (Initial and Reflection Explanation) and the pre-/posttest item, Energy Story

Score and criteria	Embedded Assessment Sample Response	Energy Story Sample Response
1: Off-task	"STuff"	"i am not really sure."
2: Ideas are relevant to photosynthesis but are non-normative or do not describe energy/matter transformations.	"It shows that energy is one of the big things that help this photosynthesis process." Notes that energy is involved, but not how it transforms during photosynthesis.	"Energy comes from the sun. Heat is how fast the atoms move. It gets absorbed. It can get cold or hot." Notes features of sunlight and energy in general, but not how it transforms during photosynthesis.
3: Basic understanding that in photosynthesis, energy and/or matter transform.	"It shows how the energy breaks apart the water molecule into hydrogen atoms and oxygen gases. Then the hydrogen atoms and the carbon dioxide combine to form water and glucose." Notes that energy is involved water splitting, but in a superficial way, without explaining where the energy goes. Hydrogen and carbon dioxide transform into glucose, but does not explain that energy is required for this transformation.	"The energy that the rabbit gets is from the sun which is called light energy. The light energy goes to the chloroplast of the plant. Then the plant goes through photosynthesis and the energy transforms into chemical energy. So when the rabbit eats the plant the energy it going inside the rabbit." Notes that energy transforms during photosynthesis, but does not explain how matter is involved in the energy transformation.
4: One complex idea: energy is required for the transformation of matter OR matter is required for the transformation of energy.	"The Photons power the water then the water breaks apart into hydrogen and oxygen. It releases the oxygen and the hydrogen powers the energy carrier and that's used to make glucose." This response details how the photons transfer energy to the water molecule, causing the molecule to split.	"Light energy comes from the sun when it hits the plant the plant uses the energy to create glucose in photosynthesis the energy turns into stored energy in the glucose and resperation [sic] turns the energy into usable chemical energy. The rabbit eats the plant and through resperation [sic] turns the stored chemical energy in the plant into usable chemical energy." Explains that energy is required for the transformation of matter: energy is used to build glucose, and that energy is then stored within the glucose.
5: Two or more examples of a complex idea: energy is required for the transformation of matter AND/OR matter is required for the transformation or transfer of energy.	"This video shows us that when water and photons enter the chlorophyll, the photons break the bonds of the water(H2O). The two water molecules break and the 2 oxygen atoms from the water molecule bond to form oxygen gas. There is a low level energy carrier on an energy wheel. When the 4 hydrogen atoms break and go on the energy wheel, their energy is transferred to the energy carrier, which goes to the glucose machine. This process is repeated 6 times to create 24 hydrogen atoms, and get enough full energy carriers to run the glucose machine and create glucose. Then, the 24 hydrogen atoms along with 6 carbon dioxide molecules go into the glucose machine and create glucose, along with 6 water molecules." This answer includes complex ideas: the hydrogens transfer energy to "energy carriers" (matter is required for the transfer/transformation of energy), and this energy then transforms hydrogen and carbon dioxide into glucose and water (energy is required for the transformation of matter).	"The Rabbit gets energy from the sun through the plant. The energy coming from the sun in light waves is called solar energy. The chloroplast in the plant uses this energy in photosynthesis to separate h2o molecules. After it has done this the energy transforms into kinetic energy which in photosynthesis is used to combine the co2 and hydrogen molecules to get glucose. Then the kinetic energy transforms into chemical energy which the plant's mitochondrion needs so it breaks apart the glucose molecules to get usable chemical energy therefore when the Rabbit eats the plant it gets that usable chemical energy as well, which at first came from the sun." Complex ideas: both energy and matter are transformed when water molecules are split (light to kinetic energy, a water molecule to atoms); both are transformed again when glucose is built (kinetic energy to chemical energy, carbon dioxide and hydrogen to glucose).

We used 92 student responses to the unit-embedded, Initial and Reflection Explanation, items associated with the photosynthesis animation to develop the Energy-Matter Rubric. Answers were scored from 1 (off-task) to 5 (two or more complex ideas about matter or energy transformation) (Table 3). We developed sub-rubrics to identify complex ideas related to the key moments or to the photosynthesis process overall (Appendix A).

To measure the reliability of the rubric, the first two authors double coded four sets of 30 randomly selected responses, discussing and resolving disagreements after each set. Much of the discussion related to how we credited students' expression of normative science ideas regarding the role of energy during the photosynthesis. We decided that in order for a response to be considered normative, and thus be assigned a score of 3 or higher, it must specifically describe how energy transformations or transferences facilitate the process of photosynthesis. On the last set, we reached 80% agreement (Kappa: 0.69). I coded the remaining responses.

Results

In this section, we present the study findings to address our research questions. First, we evaluate students' engagement with the animation and video clips. Second, we measure their ability to correctly identify the inputs and outputs of photosynthesis and to provide a mechanistic explanation of how matter is involved in energy transfer and transformation and how energy is involved in matter transfer and transformation. Third, we conduct regression analysis to determine the factors that predict student performance on the Initial and Reflection Explanation items associated with the Mechanistic Photosynthesis Animation. A confidence level of 0.05 was used for all measures of significance. Although we created and evaluated numerous model variables, we only describe the variables that were included in the final models.

Engagement with the Animation and Video Clips

All of the workgroups in the study provided on-topic responses to the guiding questions associated with the four video clips. Additionally, we observed during classroom observations active interaction with the animation playback controls and on-topic peer dialogue for the duration of the class period. As workgroups answered the video clip questions, we observed a majority of them reviewing the animation and its legend to examine the process more carefully and solidify their understanding. Indicators of student engagement includes statements like, "Let's watch it again, that was fun!" and observations of students explaining the animation to each other, summarizing the content and acting out key moments with gestures. Further, while interacting with the animation, students actively engaged in making sense of new ideas about photosynthesis. For example, when one workgroup was trying to understand why water was depicted in the animation as an additional output of photosynthesis, they drew upon their experiential prior knowledge, commenting that "if you put a bag around a plant [the bag] collects water", demonstrating their reconciliation of water as both an input and output of photosynthesis. Taken together, these results indicate that students productively engaged with the animation and video clips, suggesting that the improvements in their explanations from initial to reflection can in part be attributed to their engagement with the video clips and guiding questions about mechanism.

Understanding How Energy and Matter Transform During Photosynthesis

Photosynthesis Inputs and Outputs. To address Research Question 1, we calculated descriptive statistics of students' performance on the Inputs and Outputs pre-/post-test item. We found that, collectively, students improved in their identification of the inputs and outputs of photosynthesis, with 29% correctly identifying both at pretest, and 65% correctly identifying both at posttest (Table 4). Furthermore, the percentage of students who did not correctly identify the inputs or outputs decreased from 50% at pretest to 18% at post-test. To examine whether these results reflected individual-level rather than group-level improvement, we conducted a McNemar test (Lancaster, 1961) using paired pre- and post-test data comparing correct versus incorrect identifica-

Table 4: Frequency correct identifications of the inputs and outputs of photosynthesis (multiple choice) at pre-test and post-test, including McNemar Chi-squared for paired pre/post-test data by student.

N = 137	Pretest n (%)	Posttest n (%)	McNemar Test χ^2 (df=1)
Inputs Only	8 (6%)	8 (6%)	38.11***
Outputs Only	21 (15%)	16 (12%)	34.57***
Inputs and Outputs	40 (29%)	89 (65%)	39.36***

***p < 0.0001

tion of the photosynthesis inputs and outputs. The results were significant (p < 0.0001), indicating that over the course of the study, individual students improved in their identifications of the inputs and outputs of photosynthesis.

Mechanistic Explanations of Photosynthesis. We used the unit-embedded assessment items, Initial and Reflection Explanations to measure workgroups' understanding of how energy and matter transform during photosynthesis. Workgroups' responses to these items were scored using Energy-Matter Rubric described above.

To examine whether workgroups' and individual students' understanding of energy and matter transformation improved after engagement with the video clips and guiding questions, we conducted a McNemar-Bowker's test for symmetry on workgroups' rubric scores on the Initial and Reflection Explanation item. This results from this test indicate that shift in the number of workgroups (19 out of 66) that improved their score from a 3 or below on the Initial Explanation to a 4 or 5 on the Reflection Explanation (Table 5) is significant ($\chi^2(5) = 30.57$, p < 0.0001). Specifically, the score shift from 3 to 4, representing a change from expressing normative to both normative and mechanistic ideas was the type of shift that contributed most to the significance of the results. Notably, the number of workgroups scoring a 4 or 5 (indicating at least one complex, mechanistic idea about energy or matter transformation) more than doubled, from 17 on the Initial Explanation to 36 on the Reflection Explanation.

Scientific Explanations of the Role of Photosynthesis

To measure individual students' ability to construct a scientific explanation of the role of photosynthesis in the cycling of matter and flow of energy, and address Research Question 2, we used the Energy-Matter rubric to score students' responses to the Energy Story pre- and post-test item (Table 6). We conducted a McNemar-Bowker's test for symmetry on students' rubric scores and found that the pretest to post-test shift in students' scores is significant ($\chi^2(3) = 83.86$, p<0.0001), the most common of which was from a score of 2 to a 3 (79 students, 58%). This shift reflects an expression of normative ideas regarding the role of photosynthesis in cycling matter and flow

Table 5: Cross-tabulation table comparing workgroups' performance on the Initial and Reflection Explanation embedded assessment items.

Initial Explanation	Reflection Explanation				Total
	Score 2	Score 3	Score 4	Score 5	
Score 2	**11 (13%)**	8 (10%)	2 (2%)	0 (0%)	21 (25%)
Score 3	0 (0%)	**28 (34%)**	14 (17%)	3 (4%)	45 (54%)
Score 4	0 (0%)	0 (0%)	**10 (12%)**	6 (7%)	16 (19%)
Score 5	0 (0%)	0 (0%)	1 (1%)	**0 (0%)**	1 (1%)
Total	11 (13%)	36 (43%)	27 (33%)	9 (11%)	83 (100%)

Note: Total does not add to 100% due to rounding. **Bold**=diagonal

of energy, compared to non-normative idea expression at pretest. Notably, the number of students scoring a 4 or 5 (indicating at least one complex idea about energy or matter transformation) quadrupled from 4 at pretest to 16 at post-test. Moreover, the students in 16 of the 19 workgroups that, after engagement with the video clips and guiding questions, improved their understanding of how energy and matter transform during photosynthesis demonstrated a retention of this understanding on the Energy Story post-test item.

Table 6: Cross-tabulation table comparing workgroups' performance on the pre- and post-test Energy Story assessment item.

Energy Story Pretest	Energy Story Post-test			Total
	Score < 3	Score = 3	Score > 3	
Score < 3	29 (21%)	79 (58%)	10 (7%)	118 (86%)
Score = 3	2 (1%)	9 (7%)	4 (3%)	15 (11%)
Score > 3	0 (0%)	2 (1%)	2 (1%)	4 (3%)
Total	31 (23%)	90 (66%)	16 (12%)	137 (100%)

Note: Total does not add to 100% due to rounding.

Further exploration using cross-tabular analysis showed that 53 (85%) of the 62 students who scored high (4 or 5) on the Reflection Explanation also expressed normative and/or mechanistic ideas (score 3, 4, or 5) on the Energy Story item at post-test (Table 7). Moreover, 75% (12) of the students who scored a 4 or 5 on the Energy Story item at post-test also scored a 4 or 5 on the Reflection Explanation item. Moreover, 75% (12) of the students who scored a 4 or 5 on the Energy Story item at post-test also scored a 4 or 5 on the Reflection Explanation item. This distribution was statistically significant as determined by a Fisher's exact test and Bonferroni correction ($p = 0.005$).

Table 7: Cross-tabulation table comparing workgroups' performance on the Reflection Explanation embedded assessment item and post-test Energy Story item.

Energy Story Post-test	Reflection Explanation		Total
	Score <4	Score 4 or 5	
Score 2	22 (16%)	9 (7%)	31 (23%)
Score 3	59 (43%)	41 (30%)	90 (66%)
Score 4 or 5	4 (3%)	12 (9%)	16 (12%)
Total	75 (55%)	62 (45%)	137 (100%)

Note: Total does not add to 100% due to rounding.

Learning from the Mechanistic Photosynthesis Animation

The above analysis shows that workgroups' explanations of the cycling of matter and flow of energy during photosynthesis improved after their engagement with the video clips and guiding questions about key moments of energy and matter transformation. To explore factors that may have contributed to students' learning from the Mechanistic Photosynthesis Animation and scaffolded instruction, we constructed three multiple logistic regression models. Given our relatively small sample size, we reduced the number of variables in each model by first creating univariate models for each variable, then included in the final model all variables that were statistically significant (Bendel & Afifi, 1977). For each final model, the regression coefficients were exponentiated to give estimated odds ratios. Additionally, we used a cluster option for students' workgroup ID to generate robust standard errors as a way to account for the variation in grouping from pre-/post-test (individual) to unit engagement (workgroups).

Explaining Initial Performance. We investigated whether students' performance on the pretest assessment items (i.e. Energy Story, Inputs Only, Outputs Only, and Inputs and Outputs), their teacher, or their study condition assignment had explanatory power for their performance on the

Initial Explanation embedded assessment item. We used the teacher as an explanatory variable because during classroom observations we noticed differences in the interventions that teachers provided. For example, one teacher was observed evaluating students' animation explanations and encouraging them to attend more carefully to the details of the animation. Given the relatively few number of extremely low and high scores for the Initial Explanation and Energy Story items, we created dichotomized variables for workgroups' performance on each of these items. We chose a KI score of 4 as the threshold value for dichotomization, since a KI score of 4 indicated that a response exhibited both mechanistic reasoning and an understanding of the interdependence of energy and matter transformations. The reference group for the Energy Story score variable was students who scored a 1 or 2 on this item. The reference group for Teacher was Teacher 1, who we did not observe providing workgroups with oral encouragement and guidance to revise their Initial Explanation response. Given its theoretical significance for the study, we included the variable for teacher in the final model, irrespective of its statistical significance. Since only 19 students (14%) had normative energy-matter ideas at pretest, we decided to exclude the variable for performance on the Energy Story item from the model to increase model reliability.

Table 8: Explaining Performance on Initial Explanation Model, multiple logistic regression model (cluster robust standard errors) for scoring higher than a 3 on the Initial Explanation embedded assessment item, using pretest performance, study condition, and teacher as explanatory variables.

Factors in the Model (Variable type, values)	Odds Ratio (cluster robust std. error)	z-score	p-value	[95% Conf.Interval]
Correctly selected both the inputs & outputs on the Photosynthesis Inputs/Outputs Pretest item (binary, 1-yes or 0-no)	3.05 (1.37)	2.48	0.013*	1.26 - 7.36
Having the teacher provide guidance for revising the Initial Explanation (binary, 1-Teacher 2; 0-Teacher 1	1.54 (0.90)	0.73	0.462	0.49 - 4.86

Notes: Cluster robust standard errors were used since students provided the Initial Explanation in workgroups but completed the pretest items individually.
* p-value significant at 0.05 level

The explanatory model for performance on the Initial Explanation item (Table 8) revealed that, after controlling for all other factors in the model, students who correctly selected both the inputs and outputs of photosynthesis on the pretest had 3.05 times as great the estimated odds of getting scoring a 4 or 5 on the Initial Explanation item as students who selected incorrect photosynthesis inputs or outputs on the pretest. This estimated odds ratio was statistically significant (Inputs+Outputs: 95% CI from 1.26 to 7.36, $z = 2.48$, $p = 0.013$), and no other factors in the model were statistically significant.

Explaining Reflection Performance. To investigate the factors associated with students' performance on the Reflection Explanation embedded assessment item, we constructed a multiple logistic regression model using students' performance on the Reflection Explanation embedded assessment item as the response variable. Given the relatively few extremely low and high scores, we also created a dichotomized variable for Reflection Explanation. Similar to what we did for the Initial Explanation and Energy Story variables, we used a KI score of 4, representing both mechanistic reasoning and an understanding of the interdependence of energy and matter transformations, as the threshold value for dichotomization. In addition to using all the same explanatory variables, we evaluated the dichotomized variable for performance on the Initial Explanation item to determine if students' performance on the Initial Explanation item could explain their performance on the Reflection Explanation item. However, in the final model the variable for Initial Explanation performance was excluded because of collinearity.

Table 9: Explaining Performance on Reflection Explanation Model, multiple logistic regression model (cluster robust standard errors) of scoring high on the Reflection Explanation embedded assessment item using pretest performance, and teacher as explanatory variables.

Factors in the Model (Variable type, values)	Odds Ratio (cluster robust std. error)	z-score	p-value	[95% Conf.Interval]
Correctly selected both the inputs & outputs on the Photosynthesis Inputs/Outputs Pretest item (binary, 1-yes or 0-no)	2.52 (0.96)	2.43	0.015*	1.20 - 5.33
Study Condition (binary, 1-Open-Response; 0-Multiple-Choice)	0.86 (0.41)	-0.32	0.747	0.34 - 2.19
Having the teacher provide guidance for revising the Initial Explanation (binary, 1-Teacher 2; 0-Teacher 1	1.89 (0.90)	1.34	0.181	0.74 - 4.83

Notes: Cluster robust standard errors were used since students provided the Initial Explanation in workgroups but completed the pretest items individually.
* p-value significant at 0.05 level

Similar to the Initial Explanation regression model, the Reflection Explanation model (Table 9) revealed that, after controlling for all other factors in the model, only the variable for knowing both the inputs and outputs of photosynthesis on the pretest had an estimated odds ratio that was significantly significant (Inputs: 95% CI from 1.29 to 8.32, z = 2.50, p = 0.012). Specifically, students who correctly selected both the inputs and outputs had 2.53 times as great the estimated odds of scoring a 4 or 5 on the Initial Explanation item as students who selected incorrect photosynthesis inputs or outputs on the pretest.

Explaining Post-test Energy Story Performance. To explore the factors that might have contributed to students developing an integrated understanding of the role of energy in the cycling of matter and flow of energy, we constructed a multiple regression model using students' performance on the Energy Story post-test item as the response variable. This response variable was dichotomized using a score of 2 as the threshold, effectively dividing scored responses between those expressing normative or mechanistic ideas and those expressing non-normative ideas. In addition to the variables evaluated in the previous models, we also created a three-category (low, medium, high) variable for students' performance on the Reflection Explanation item. The threshold values for the categories were as follows: low - < 3, representing the expression of non-normative ideas; medium - 3, representing normative but non-mechanistic or linked ideas; high > 3, representing normative, mechanistic, and linked ideas. The reference group for the Reflection Explanation variable was the "low" category. Additionally, we created a dichotomous variable for whether students knew any combination of inputs and outputs on the Inputs and Outputs pretest item.

Table 10: Explaining Performance on Energy Story Model, multiple logistic regression model (cluster robust standard errors) of not scoring low on the Energy Story post-test item using pretest performance, Reflection Explanation performance, study condition, and teacher as explanatory variables.

Factors in the Model (Variable type, values)	Odds Ratio (cluster robust std. error)	z-score	p-value	[95% Conf.Interval]
Reflection Explanation performance (categorical, 2-score > 3; 1-score = 3; 0-score < 3	1: 2.57(1.43) 2: 4.31(2.56)	1: 1.70 2: 2.46	1: 0.089 2: 0.014*	1: 0.87 - 7.66 2: 1.34 - 13.83
Correctly selected both the inputs & outputs on the Photosynthesis Inputs/Outputs Pretest item (binary, 1-yes or 0-no)	5.72 (3.09)	3.23	0.001**	1.99 - 16.47
Study Condition (binary, 1-Open-Response; 0-Multiple-Choice)	0.74 (0.15)	-1.48	0.140	0.49 - 1.11
Having the teacher provide guidance for revising the Initial Explanation (binary, 1-Teacher 2; 0-Teacher 1	0.67 (0.27)	-1.00	0.319	0.30 - 1.48

Notes: Cluster robust standard errors were used since students provided the Initial Explanation in workgroups but completed the pretest items individually.

* p-value significant at 0.05 level

** p-value significant at 0.01 level

In the final Energy Story model (Table 10) the variables for scoring high on the Reflection Explanation item and selecting any or all of the correct inputs and outputs of photosynthesis on the Inputs and Outputs pretest item were statistically significant. After controlling for all other variables in the model, students who scored a 4 or 5 on the Reflection Explanation item had 4.31

times as great the estimated odds of scoring a 3 or higher on the Energy Story as students who scored a 3 or below (95% CI from 1.34 to 13.83, z = 2.46, p = 0.014). Students who correctly identified the inputs or outputs, or both, had 5.72 times as great the estimated odds of scoring a 3 or higher on the Energy Story, after controlling for all other variables in the model, as students who were unable to correctly identify the inputs or outputs (95% CI from 1.99 to 16.47, z = 3.23, p = 0.001). The other two variables in the final model, Teacher and Study Condition, were not statistically significant.

Discussion

In this classroom study, we used the Knowledge Integration framework to develop and evaluate instructional scaffolds for the Mechanistic Photosynthesis Animation, which was designed to support middle school students in seeing, exploring, and understanding the intangible details associated with how energy and matter transformation in photosynthesis. Guided by seven research-based design principles, the Mechanistic Photosynthesis Animation aligns with the NGSS goal of supporting students to develop a robust and coherent understanding of energy and matter transformation during photosynthesis.

Developing a Mechanistic Understanding of Energy and Matter Transformation

We conjectured that supporting students to understand the mechanism of energy and matter transformation would allow them to move beyond knowledge of why photosynthesis occurs towards a sophisticated understanding of how photosynthesis occurs. To evaluate this conjecture, we analyzed students' responses to unit-embedded assessments in our study instruction.

Accessible, Mechanistic Presentation Promotes Sophisticated Understanding. This instruction began by engaging students with our Mechanistic Photosynthesis Animation (under review, 2020) and research-based instructional scaffolds. The animation was designed to depict the mechanism of photosynthesis using language and analogies that students could easily understand. Students were then prompted to generate a written explanation of the flow of energy through the photosynthesis process. Our analysis revealed that on the Initial Explanation, 75% of the student workgroups were able to provide normative ideas regarding the process of photosynthesis and 27% of those workgroups were able to provide a mechanistic explanation of the process. Workgroups' mechanistic explanations provided details for the interconnected nature of energy and matter transformations during key parts of the photosynthesis process (e.g. "When the 4 hydrogen atoms break and go on the energy wheel, their energy is transferred to the energy carrier..."). Such sophisticated explanations were likely mediated by engagement with the Mechanistic Photosynthesis Animation as this level of detail was provided nowhere else in the unit or in the teachers' instruction up to that point. While it is possible that students had this level of understanding prior to instruction, it is unlikely given that only 14% of students were able to express normative ideas about photosynthesis at the organism level (i.e. on the Energy Story item), the level at which photosynthesis is introduced during elementary instruction (National Research Council, 1996, 2013).

Immediately after answering the Initial Explanation item, students explored the process more closely by answering guided questions associated with four video clips of the animation, with each clip capturing a key moment in the process of energy and matter transformation. Students were randomly assigned to either the Multiple-Choice or Open-Response study condition in which they were either provided with a detailed description of what was happening in the clips then asked to answer a multiple-choice version of the guiding question or they were prompted to generate their own response to the guiding question, respectively. Based on our classroom observation data (e.g. enthusiastic exclamations, dynamic partner dialogue), students found the Mechanistic Photosynthesis Animation and video clips to be fun and accessible which seemed to support their active learning. These results substantiate our design decisions to use sound effects, everyday language, common analogies (e.g. hoops, wheels, machines; sense-making principle-1: accessible representations/language) and include video playbacks for the animation and clips (sense-making principle-3: differential exploration).

Generating plus Revising Enhances Student Understanding. After engaging with the video clips and guiding questions, students were shown the full animation again and presented with a prompt to revise their Initial Explanation, which was automatically imported into the answer space. Our instantiation of the process management design principle to automate non-salient tasks (e.g. rewriting the initial response) seemed to facilitate the science practice of revision, as 83% of the 101 workgroups in the study chose to revise their Initial Explanation responses. The quality of workgroups' revision was evident in the significant shift in their score from the Initial to Reflection Explanation. Specifically, 40% of workgroups made revisions that reflected an improved understanding of the photosynthesis process, with 40% of those students gaining a mechanistic understanding. This relatively high percentage of students substantively revising their ideas after engagement with the video clips and guiding questions is notable given that revision has been identified as a difficult practice for students, especially in middle school, to effectively engage in (Bridwell, 1980; Crawford et al., 2008).

The result that 43% of workgroups scored a 4 or 5 on our KI rubric on the Reflection Explanation item (compared to 20% on the Initial Explanation) demonstrates that after serious engagement with the animation, video clips, and instructional scaffolds middle school students can explain how the transformation and transference of energy during photosynthesis facilitates the atomic rearrangement of carbon dioxide and water to form glucose and oxygen gas. These results challenge the prevailing ideology that middle school students are best served by omitting the mechanism of photosynthesis from instruction and substantiate our decision to design the guiding questions to support mechanistic reasoning (e.g. Clip 2: "Watch the hydrogens in the clip below. Where did the energy wheel get the energy to turn?"; sense-making principle 2-disciplinary semantics). Additionally, the results from our model analysis, namely that study condition was not a statistically significant explanatory factor for workgroups' Reflection Explanation performance, suggests that the inclusion and design of the video clips and guiding questions rather than the format in which students provided their responses was more valuable toward workgroups developing an integrated understanding of energy and matter transformations during photosynthesis. This result nuances the findings of Ryoo Linn (2014), where students who generated explanations of the photosynthesis process achieved higher learning gains than students who selected predetermined responses. Specifically, it suggests that while generating an explanation of complex processes is valuable during the initial explanation (i.e. sense-making) attempt, it is not needed during subsequent instructional scaffolds. It also highlights the value of students revising their generated ideas when developing an understanding of the complex science ideas.

Minimal Prior Knowledge Need for Developing a Normative, Mechanistic Understanding. Our explanatory models for workgroups' performance on the Initial and Reflection Explanation items also showed that students can develop a mechanistic understanding of energy and matter transformation during photosynthesis by viewing the Mechanistic Photosynthesis Animation even if they only know the basic information like the inputs (i.e carbon dioxide, water, and light) and outputs (i.e. glucose and oxygen) of the photosynthesis reaction. Specifically, we found that knowing both the inputs and outputs of photosynthesis at pretest positioned workgroups to have 3.05 times as great the estimated odds of expressing normative, mechanistic ideas after engaging with the Mechanistic Photosynthesis Animation the first time as students who did not know both inputs and outputs. These results highlight the value of instructional supports that build on students' prior ideas, as they suggest that students could connect ideas in the animation to ones they already held (i.e. the animation ideas were accessible). Perhaps knowing the inputs and outputs, which 29% of students in this study did, allowed them to attend more closely to the mechanism of photosynthesis in order to understand how the inputs become the outputs. The video clips and guiding questions for the key mechanistic moments might have functioned as effective scaffolds for their careful attention to the mechanism as there was no prior instruction in the unit to support students in gaining a mechanistic understanding of the process and knowing the inputs and outputs was the only factor in the Reflection Explanation model that was statistically significant. That teacher was not a statistically significant explanatory factor for students' Reflection Explanation performance suggests that teacher guidance for the revision process was not a significant factor for students' being able to develop a normative, mechanistic understanding of photosynthesis. Our observation that both teachers provided students with feedback regarding their performance suggests that supporting students' in the sense-making process may be a valuable pedagogical action for teachers to take in helping their students develop sophisticated science ideas.

The finding when building the Reflection Explanation model that workgroups' performance on the Initial Reflection item perfectly explained their performance on the Reflection Explanation item, demonstrates that students retained their normative, mechanistic understanding photosynthesis even after engagement with the video clips and guiding questions. But differently, the design of the video clips and guiding questions did not interfere with the sense-making constructs that workgroups made during their initial attempts to learn from the Mechanistic Photosynthesis Animation. This finding is significant given research that shows how scaffolds can inhibit the learning of students who already have a high level of understanding (i.e. expert reversal effect; (Kalyuga et al., 2003).

Constructing Scientific Explanations for the Role of Photosynthesis

The Initial/Reflection Explanation and guiding questions for the video clips supported students in articulating and reflecting on their developing ideas throughout the investigation and represented our strategy for implementing the scaffolding guideline for these scientific inquiry processes (i.e. facilitating ongoing articulation and reflection). We also conjectured that developing a sophisticated understanding of how photosynthesis occurs would allow students to meet the NGSS performance expectation of constructing a scientific explanation of the role of photosynthesis in the cycling of matter and flow of energy into and out of organisms. To evaluate this conjecture, we analyzed students' performance on the Energy Story item before (pretest) and after engagement with the study instruction (post-test).

Our analysis revealed that 85% of students were able to maintain the normative understanding they developed from the mechanistic animation and scaffolds to the end of instruction as evidenced by their score of 3 or higher on the Energy Story post-test item. A significant portion of these students (23%) were able to maintain a mechanistic understanding.

Although students engaged the animation and scaffolds in groups, when evaluated at the individual level, the majority demonstrated an improvement in their understanding of how energy is transferred and transformed from sunlight to usable chemical energy in an animal cell, and how matter transforms in the process from pretest (14% expressed normative ideas) to post-test (77%).

Unlike the results from the Initial and Reflection models, our explanatory model for performance on the Energy Story post-test item showed that as long as students knew either the inputs or the outputs of photosynthesis, they had 5.72 times as great the estimated odds of expressing normative ideas about how photosynthesis facilitates the cycling of matter and flow of energy as students who did not know this basic information upon starting instruction. Importantly, expressing a normative, mechanistic understanding of photosynthesis on the Reflection Explanation item was also a statistically significant factor for being able to express normative ideas about the role of photosynthesis at post-test, with students having such an understanding having 4.31 times the estimated odds of being able to do so as those without. These results identify two viable paths for developing normative ideas about the role of photosynthesis in the cycling of matter and flow of energy, namely via knowing either inputs and outputs of photosynthesis (i.e. starting knowledge) and via developing a mechanistic understanding of energy and matter transformation during photosynthesis (i.e. scaffolded mechanistic instruction). The first route corresponds to the current learning progression, where students are taught the basics of photosynthesis in elementary such that they can enter 7th grade with knowledge of the inputs and outputs. This current learning progression manifested in this study as 50% of students knowing at least the inputs or outputs at pretest. However, the second route corresponds to the approach taken in this study, which has the added benefit of supporting students in developing a sophisticated (i.e. mechanistic) understanding of how photosynthesis facilitates the cycling of matter and flow of energy. The added benefit was reflected in the finding that 20% of students who exhibited a normative, mechanistic understanding on the Reflection Explanation item also exhibited a normative, mechanistic understanding on the Energy Story item at post-test, as compared to 5% of students who did not exhibited a normative, mechanistic understanding on the Reflection Explanation item. According to our results the prior knowledge needed to access this second route is knowledge of both the inputs and the outputs of photosynthesis. Therefore, if a modest adjustment is made in the current instruction such that students enter middle school knowing both inputs and outputs, then students can potentially be well positioned to not only develop sophisticated scientific knowledge earlier but continue to do so as they engage more complex ideas in the future.

Principles for Developing Effective Molecular-level Animations for Middle School Students

Draw upon a diverse design team. The ability of our Mechanistic Photosynthesis Animation to provide this intermediate molecular-level understanding stands in contrast to other available internet resources targeted towards middle school students which either over- or undershoot the requisite cognitive engagement. Our success in designing an animation to support middle school students in developing a mechanistic understanding of photosynthesis and its key moments of energy and matter transformation reflects the great value of having a design team with diverse expertise. The educational researchers provided guidance regarding the inclusion of research-grounded instructional scaffolds, and the technology team supported the development of the animation and its incorporation into the WISE platform. The content experts provided guidance regarding the scientific accuracy of the animation content, and the teacher and students gave feedback about its appropriateness for the middle school classroom context.

Scaffold for sense-making and process management. Furthermore, our result that after engaging with the video clips and guiding questions over a third of workgroups developed a sophisticated understanding of energy and matter transformation during photosynthesis highlights the value of providing students with opportunities to distinguish amongst their prior and developing ideas, a key tenet of the Knowledge Integration framework and key design principle for creating instructional scaffolds to accompany animations. By drawing upon everyday language and incorporating structural and functional analogies, our Mechanistic Photosynthesis Animation made learning the complex concepts of energy and matter transformation accessible to middle school students. By deconstructing the full animation into video clips with associated guiding questions, we highlighted the key events in terms of energy and helped students both distinguish among parts of the animation and attend to the salient features of the process. Additionally, the playback and navigation controls supported students to autonomously learn from animation and video clips.

Scaffold for articulation and reflection. The open-ended assessment items provided students with opportunities for reflection and revision during the sense-making process. Together, these features allowed our Mechanistic Photosynthesis Animation to support students in developing an intermediate molecular-level understanding of the photosynthesis process and function as a "stepping-stone understanding" (Duncan & Rivet, 2013) in the learning progression toward a deeper biochemical understanding of living systems.

Study 2 Conclusions

By drawing upon everyday language and incorporating structural and functional analogies, the Mechanistic Photosynthesis Animation made learning the complex concepts of energy and matter transformation accessible to middle school students. Deconstructing the full animation into video clips with associated guiding questions functioned to highlight the key events in terms of energy and helped students both distinguish among parts of the animation and attend to the salient features of the process. Additionally, the playback and navigation controls supported students to autonomously learn from animation and video clips, and the open-ended assessment items provided them with opportunities for reflection and revision during the sense-making process.

Limitations

Although the relatively small number of teachers and students in this study may limit the generalizability of our results, the pretest performance of the students in this study is similar to performance of middle school students in the many, representative schools in our prior investigations (Ryoo & Linn, 2012; Ryoo & Bedell, 2017). Moreover, our finding that, at pretest, roughly a third of students knew both the inputs and outputs of photosynthesis aligned with other research findings (Marmaroti & Galanopoulou, 2006). Furthermore, students scored in the low range on all pretest assessments related to energy and matter transformation as would be expected given the exclusion of a mechanistic study of photosynthesis in primary school science instruction. Nevertheless, additional studies should be conducted with more schools and students to support the extension of our findings to other contexts.

We also recognize the limitations of significance of the explanatory factors in our models given the rather large confidence intervals associated with these factors. While the results presented in this study were significant there is more to explore regarding the factors that contributed to student performance. Perhaps there were other factors for which knowing both the inputs and outputs served as proxies that were responsible for students' ability to develop a normative, mechanistic understanding of photosynthesis after engaging the Mechanistic Photosynthesis Animation. Alternatively, perhaps the teacher-assigned workgroups allowed students to learn from each other in ways that would not have been possible had they worked individually. Another area of further exploration is the role of teacher-supported sense-making, as we observed both teachers in this study providing students with feedback regarding their learning progress.

We further acknowledge that our Mechanistic Photosynthesis Animation and instructional scaffolds did not support all students in this study to develop a sophisticated understanding of energy and matter transformation during photosynthesis. Although most students (62% scored a 3 or above on the Reflection Explanation) developed an understanding of the type of energy and matter transformation that takes place during photosynthesis (i.e. light energy to chemical energy; carbon dioxide and water to glucose and oxygen), there is still a need to investigate how to best support all students. Finally, we did not investigate this approach beyond photosynthesis. Future work should investigate how animating energy and matter transformations in other science contexts can help middle school students to develop a mechanistic and molecular-level understanding of complex natural phenomena across science disciples.

Chapter 2 Summary

The photosynthesis unit used in these studies was developed by researchers and used to supplement classroom instruction on energy and matter transformation during photosynthesis. Although education researchers draw on current disciplinary and learning sciences research to design curriculum that can support the development of integrated knowledge about energy and matter, the complexity of the classroom learning context warrants the inclusion of teachers' classroom teaching expertise.

In light of this reality, new models for developing curriculum for classroom use are being investigated. One promising model is curriculum development via researcher-practitioner partnerships (RPPs) (Penuel & Gallagher, 2009). This model aims to leverage the expertise and insights of researchers and classroom educators toward developing curriculum that can further enhance student learning in the complex environment of classrooms.

In chapter 3, I describe the design and implementation of an RPP-based model used to co-design a revision of the WISE photosynthesis unit used in the studies presented in this chapter. I also describe teachers' implementation of the co-designed unit in their classroom instruction.

CHAPTER 3 - LEVERAGING A RESEACHER-PRACTITIONER PARTNERSHIP TO CO-DESIGN CURRICULUM FOR TECHNOLOGY-ENHANCED SCIENCE CLASSROOMS

Chapter 3 Overview

Since its publication in 2013, the NGSS has been widely adopted by U.S. states (National Research Council, 2013), often without accompanying curriculum materials. During initial implementation of WISE units, many teachers reported interest in better aligning their instruction with NGSS, thus motivating this study. Given the new, three-dimensional learning goals of the NGSS, developing curricula de novo that can support students to meet these ambitious standards is a formidable task, even for the most adept teacher. In their instructional comparison study, Penuel and Gallagher (2009) showed that when teachers assume the role of curriculum customizer rather than designer, they produce higher quality curriculum, as measured by its ability to support inquiry and promote student science understanding.

In the following sections, I describe a study that builds on literature findings toward increasing teachers' capacity to co-design by customizing existing curricula.

STUDY 3 - AN RPP-BASED MODEL FOR REDESIGNING THE WISE PHOTOSYNTHESIS UNIT

Introduction

We[2] report on the design and impact of a professional development workshop that positions teachers and researchers as collaborative partners in customizing WISE units to align with the NGSS. To the workshop, teachers brought their teaching expertise and used their experience implementing the units and logged student data to improve the unit. Researchers brought their expertise in designing the units following the Knowledge Integration (KI) pedagogical framework and used the framework to guide the professional development activities. We hypothesized that, if aligned with curriculum activities, the four steps of the KI process (i.e. eliciting ideas, adding ideas, distinguishing ideas, and reflecting on ideas) would serve as instructional strategies and scaffold teachers' application of the underlying constructivist theory of learning. We further hypothesized that, if aligned with the workshop activities, the four KI steps would give teachers and researchers an experiential knowledge of the process, facilitate the integration of their respective knowledge, and foster the collaborative customization (i.e. co-design; Roschelle et al., 2006) of WISE units for NGSS-alignment and variegated classroom implementation. We discuss how the results from this study informed the design of an online interface on the WISE platform to support teachers to customize and implement NGSS-aligned curricula in ways that helps students develop coherent, three-dimensional science knowledge.

Background

Since its publication in 2013, the NGSS (National Research Council, 2013) has been widely adopted by U.S. states, often without accompanying curriculum materials. During initial implementation of WISE units, many teachers reported interest in better aligning their instruction with NGSS, motivating this study. Given the new, three-dimensional learning goals of the NGSS, developing curricula de novo that can support students to meet these ambitious standards is a formidable task, even for the most adept teacher. In their instructional comparison study, Penuel and Gallagher (2009) showed that when teachers assume the role of curriculum customizer rather than designer, they produce higher quality curriculum, as measured by its ability to support inquiry and promote student science understanding. Building on these findings, we designed a knowledge integration workshop to build teachers' capacity to customize existing curricula rather than design new curricula.

A review of professional development supporting teachers to use technology-enhanced science inquiry curricula found a significant effect for programs that followed the KI framework (Gerard et al., 2011). Successful professional development efforts elishortcited teachers' ideas, added new ideas to their existing repertoire, and encouraged teachers to distinguish among their ideas, reflect upon their experiences, and develop an integrated, coherent view of instruction (Linn et al., 2011). The KI framework draws on extensive research supporting a socio-constructivist view of learning.

A key tenet of socio-constructivist learning and knowledge integration is sustained collegial collaboration. In successful professional development efforts, this collaboration involves teachers

[2] I switched to the first-person plural here and throughout the remainder of this chapter, excluding the Chapter Summary, as an acknowledgement of the collaborations that informed the studies presented herein, namely Wiley, Bradford, and Linn, 2019

from multiple schools along with university mentors (Penuel & Gallagher, 2009)). As teachers collaborate with other education community members in activities such as customization, they negotiate meaning (Lave, 1996), which is a critical aspect of learning.

Research Questions

Research suggests the value of focusing on the customization of existing curriculum materials. However, supporting teachers to incorporate the NGSS into their teaching practices calls for new models of professional development. The KI framework as a professional development model offers promise, especially for the customization of WISE units, since they were designed using the KI framework. Thus, we investigated the following research questions:

1. Can the KI framework guide the design of both curriculum customization and professional development?

2. Which professional development activities:

   (a) Enable teachers to use pedagogical principles to align existing curriculum materials with NGSS?

   (b) Support teachers and researchers to collaborate to develop curriculum that enables students to meet the three-dimensional learning goals of the NGSS?

Methods and Materials

We designed and tested professional development activities consisting of a 1.5-day workshop to review and customize WISE units, in-class support during implementation of the customized unit, and post-implementation interviews. The professional development activities followed the KI pedagogy of eliciting ideas about teaching the unit, adding new ideas to customize the unit, distinguishing among ideas during implementation of the customized unit, and reflecting on the experience.

Participants

The workshop participants included 21 middle school science teachers and 15 researchers. The teachers came from 8 schools across 6 districts and the researchers came from 2 universities. All teachers had implemented at least one WISE curriculum unit prior to attending the workshop.

WISE curriculum units

WISE units are developed using the KI Framework. They elicit student ideas from their own experiences; engage students in gathering new ideas using embedded models and simulations and hands-on activities; encourage students to distinguish among these ideas by building models, testing alternative views, or critiquing ideas of others; and request reflections in reports or presentations. The WISE units used by teachers in this study are: Photosynthesis, Global Climate Change, Plate Tectonics, and Self-Propelled Vehicles. Each unit features embedded assessments, logs student responses, and captures student activities (e.g. click-stream data). Teachers and researchers can access all logged, de-identified student data via the data export interface in the Grading Tool.

Customization materials and activities

Before the workshop, in preparation for the customization process, we analyzed the WISE units to identify the NGSS performance expectations addressed in each. Then, we restructured the units into lesson series such that each lesson in the unit targeted a single NGSS performance expectation. To support coherent knowledge building for the target performance expectation, we also structured each lesson in the unit to engage students in each step of the KI process (i.e. one lesson corresponds to engagement in a complete KI cycle). The lessons were designed such that they could be taught in sequence as a unit or as independent lessons.

In addition, we created a diagrammed version of each unit consisting of a 5” x 7” notecard for each lesson with each activity in the lesson briefly described on 3” x 3” sticky notes, color-coded by each KI step (pink: Elicit Ideas; orange: Add Ideas; green: Distinguish Ideas; blue: Reflect On/Revise Ideas, Figure 6c). On the 5” x 7” notecards was the following lesson information: unit title, lesson title, recommended grade levels, targeted performance expectation, and a brief description of the learning goals. These tangible, diagrammed versions of the WISE units were the objects of customization and were designed to pilot a prototype version of a unit customization interface on the WISE platform.

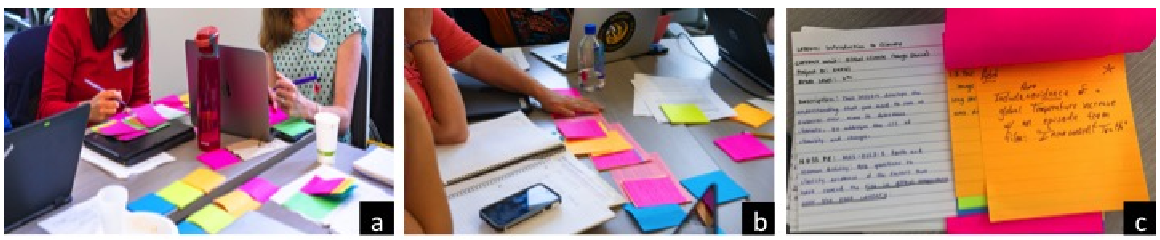


Figure 6: WISE unit customization process: (a) Identifying non-WISE, KI-aligned activities; (b) Identifying relevant activities to customize the unit; (c) Integrating their activities into the diagrammed WISE unit

After the workshop, the researchers incorporated the customizations of the diagrammed version of each unit into a complete digital version for subsequent post-workshop classroom implementation.

Data sources and data analysis

To address our research questions, we gathered data corresponding to each of the KI-aligned professional development activities. During the 1.5-day workshop, we documented the customized units for comparison to their previously implemented counterparts. Throughout the workshop, the researchers captured audio recordings and photographs of the workshop activities, and collected teachers’ written responses to the following prompts:

- What are some things you learned or have taken away from engaging in this customization process and sharing with other teachers?
- Was this customization process and reflecting on the KI cycle helpful for you in thinking about how to achieve your NGSS and other curricular goals?
- Do you think you could use this customization process for another unit you’d like to run?
- Please share any other reflections or feedback you have from the workshop.

To analyze the customization of the WISE units, we counted the number and type of interleaved KI-aligned, non-WISE activities that teachers added to the diagrammed units. Our analysis of teachers' written reflection consisted of identifying themes related to the customization and collaboration process. For this paper, we analyze the implementation of the customized WISE Photosynthesis unit as carried out by two, 7th grade teachers, Mr. Vega and Mr. Harrison. We took field notes during classroom observations and conducted post-implementation interviews to discuss their customization decisions and their overall implementation experiences. We evaluated our observation notes and interview data in terms of their implementation of the workshop customizations and the type of customizations they made during implementation.

Results

Knowledge-integrating and experiential activities

The activities of the 1.5-day workshop aligned with the four steps of the KI process and positioned teachers as experts on their teaching practice and researchers as experts on their curriculum designs. To begin the workshop, the researchers facilitated a whole group discussion to elicit ideas about the function of each dimension of the NGSS performance expectations in terms of lesson development (e.g. disciplinary core ideas provide the lesson content). During this discussion, the researchers introduced the KI framework and invited teachers to share activities they used or could KI process. This activity was designed to highlight the similarities between how the teachers and researchers conceptualize and support the knowledge building process. Each group activity of the workshop (whole group and small group) was designed to highlight the expertise of both teachers and researchers and to create opportunities for expertise sharing.

The sharing and integration of expertise was evident in the customization activity. For the unit customization activity, teachers were assigned to a small group corresponding to a unit they recently implemented and with researchers who had developed the units. Teachers were asked to think of and write on colored 3 x 3 sticky notes as many activities as they could think of for each step of the KI process (Pink: elicit ideas; Orange: add ideas; Green: distinguish ideas; Blue: reflect on/revise ideas). Teachers were invited to share their KI activity ideas with other workshop participants by placing the sticky notes on a long table centrally located in the meeting room (Figure 7). The goal of this activity was to further elicit and add ideas regarding topic-specific activities that were accessible to teachers and would support the KI process.

Figure 7: Shared interleaved teacher activities.

To further add ideas regarding unit customization, the researchers provided teachers with evidence of their students' learning. Specifically, researchers gave the teachers a random sampling of 30 of their students' responses to a post-test assessment item that targeted at least one dimension of an NGSS performance expectation addressed in the unit. Teachers were asked to evaluate the responses to identify areas of strength and weakness in their students' understanding.

The researchers then invited the teachers to customize the unit by interleaving the activities they previously wrote on the color-coded sticky notes with those on the lesson notecards. The goal of this activity was to customize the unit in ways that would better support students in developing an integrated understanding of the targeted NGSS performance expectation, using evidence of previous student learning as a point of reference. Teachers were given full license to eliminate, substitute, or add any KI-supporting activity by rearranging the sticky notes on the lesson notecards. In this way, teachers could distinguish their ideas about how to customize the unit in ways that would support their students in the KI process and function within their classroom constraints and resources (Figure 6a, 6b).

Teachers worked collaboratively within and across their small groups to exchange ideas and activities to customize their unit. Of all the customizations that teachers made across all the units, 33% (31/94) would elicit students' ideas, 33% (31/94) would add to students' ideas, 10% (9/94) would support students in distinguishing their ideas, and 24% (23/94) would help students reflect on or revise their ideas (Figure 8).

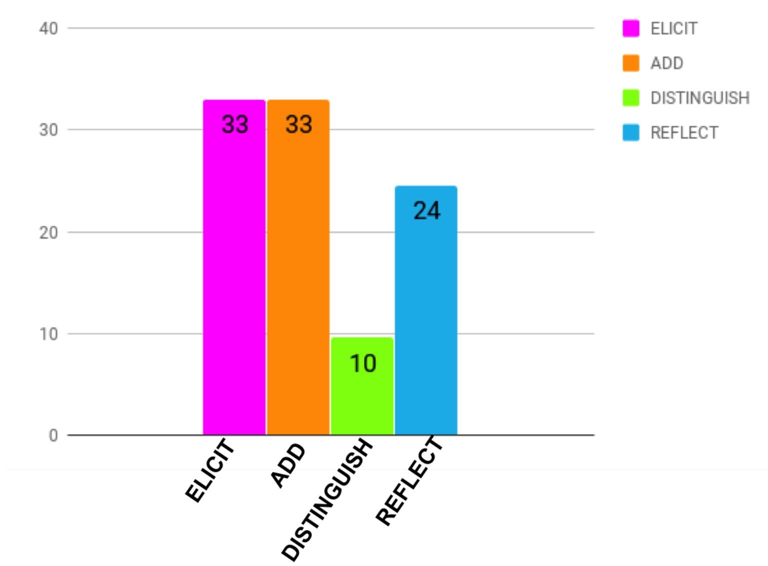


Figure 8: Percentage of unit customizations aligned to each Knowledge Integration step.

In another group workshop activity, teachers were asked to evaluate whether their customized unit would support their students in developing an integrated understanding of the disciplinary core ideas, cross cutting concepts, and science or engineering practices targeted in the unit lessons. After teachers made their final customizations, they were invited to share their customized units with other teachers who were interested in implementing the unit. During this unit exchange activity, teachers were able to get feedback from other workshop participants about their customization decisions.

In the final group workshop activity, the researchers demonstrated and helped teachers use the unit authoring tools currently built-in into the WISE platform. During these small workgroup sessions, teachers chose 1-2 customizations to reify in the digital version of the unit on the WISE platform.

To conclude the workshop, teachers were asked to provide their reflections on their workshop experiences. Of the 21 teacher participants, 15 (71%) provided responses to the reflection quetsions. As for whether the KI framework was a productive lens through which to evaluate and customize a unit, 80% of teachers (12/15) answered in the affirmative. In response to the question, "Do you think you could use this process again to customize another unit you'd like to run?", 87% of teachers (13/15) answered in the affirmative. Additionally, many teachers (87%, 13/15) shared that the lesson series format of the WISE units provides great affordances for customization using their own activities.

Reflection on and implementation of a customized unit: The cases of Mr. Vega and Mr. Harrison

To continue exchanging expertise after the workshop and to extend the collaborative customization efforts, I provided in-class support during implementation of the customized unit. The following are the results of the implementation of the customized Photosynthesis WISE unit (`https://wise.berkeley.edu/project/24548`) in the fall term after the summer workshop by two teachers, Mr Vega and Mr. Harrison. Mr. Harrison worked in the small group that customized the Photosynthesis unit during the summer workshop, however Mr. Vega worked in the small group that customized the Global Climate Change unit. Over the course of implementation of the customized Photosynthesis unit, I noticed how both teachers interleaved non-WISE activities, most of which were designed to provide students with additional ideas to supplement their limited prior knowledge about certain topics, like chemical reactions. This observation supports the analysis of the unit customizations made during the workshop where 33% of the total customizations aligned with the Adding Ideas step of the KI process (Figure 8). In both cases, the teachers used a molecular modeling kit to provide their students with ideas about atoms, molecules, and the nature of chemical reactions related to photosynthesis. Additionally, Mr. Harrison incorporated a multi-modal activity on the conservation of matter during the photosynthesis reaction as a transition from Lesson 1 (Plant Growth Needs) to Lesson 2 (Photosynthesis and Cellular Respiration Reactions). During the post-implementation interview he commented that he used the WISE concept mapping activities to support his students in distinguishing their ideas about energy and matter cycling, the targeted cross-cutting concept in the unit. Mr. Harrison's use of WISE activities over his own activities to help students distinguish their ideas correlates with the result from the customization activity, namely the low levels (10%) of customization activities aligning with the distinguishing step (Figure 8). This finding also parallels Mr. Vega's reflection comment that he plans to "[s]trengthen the role WISE plays during the Distinguishing...phase".

Mr. Harrison: A deeper look. During the workshop, Mr. Harrison expressed reticence regarding the customization partnership. His past experiences with the units led him to feel like they were "adapted to fit the need of each researcher", additionally he could not see how the digital version of the WISE unit could be restructured into related but independent lessons aligned to specific NGSS performance expectations. However, when asked how he thought the customized, digital Photosynthesis unit aligned with the NGSS he remarked, "It's definitely aligned, it fits right in with our [other curriculum materials] because we go from Photosynthesis right into ecosystems" (which is Lesson 4 of the customized Photosynthesis unit). This comment highlights the way that Mr. Harrison interleaved the WISE Photosynthesis unit with his existing curriculum to better support his students in meeting the targeted NGSS performance expectations. Specifically, Mr. Harrison commented that his existing curriculum, although nominally aligned with the NGSS, did not actually provide his students with sufficient opportunities to develop a robust and coherent understanding of the targeted ideas, concepts, and practices. He, therefore, used the customized WISE unit to provide his students with these opportunities. Mr. Harrison further discussed the difficulty and discomfort he experienced when implementing curriculum that he did not develop and therefore greatly appreciated the ability to customize the WISE unit with his own activities to make the unit "his own". When Mr. Harrison was asked how the researchers could further collaborate to address his curriculum customization challenges, he offered the idea of incorporating specific WISE lessons and activities into the Google Classroom that he used to plan and organize his instruction. He stated that doing so would solve the notoriously difficult problem of trying to re-synchronize students who progress at different speeds through the WISE activities. (We elaborate upon this idea in the Conclusion section.)

Mr. Vega: A deeper look. Mr. Vega also engaged in extensive customization during implementation to assume greater "authorship" of the unit. During the implementation, he commented, "I was motivated to Edit Content to the unit...Take a look", referring to his use of the unit authoring tools on the WISE platform, a feature historically used only by researchers. In these edits, Mr. Vega customized the prompts for the concept maps to align with the topics and terminology used in his non-WISE activities. In this way, he created greater continuity between WISE and his other curriculum materials. Mr. Vega's customization of the Photosynthesis unit during implementation is of particular note since during the workshop customization activity he was not part of the Photosynthesis small group. Therefore, Mr. Vega's customization of the Photosynthesis unit demonstrates that he was able to transfer and apply the knowledge he gained during the workshop to another unit, actions that substantiated his "YES" to the reflection question of whether he could customize another unit. Beyond making edits to provide greater continuity between the WISE unit and his existing curriculum materials, Mr. Vega also applied his understanding of the KI process to all his instruction. During the post-implementation interview he stated that he used the steps of the KI process to keep track of the stage of learning in which his students were engaged and thus provide them with targeted support.

Discussion

Design principles for Knowledge Integration customization

In this study, we described professional development activities that were aligned with the KI framework and showed how the framework helped teachers customize their existing curriculum to better support their students in meeting the three-dimensional learning goals of the NGSS. The workshop reveals three design principles that we recommend for teacher-researcher professional development: support teachers and researchers to learn from each other; make thinking about customization visible; and support sustainable customization practices. In the sections below, I highlight the value of each design principle in supporting collaborative learning amongst researchers and teachers.

Supporting teachers and researchers to learn from each other

The workshop facilitated the integration of teachers' and researchers' knowledge and expertise. Throughout the workshop activities, researchers used the KI framework as a mediating tool to share their insights into the learning process, and teachers shared their insights into the instructional constraints and resources of their teaching contexts. Transitioning from whole to small group activities allowed workshop participants to learn from each other and consider new strategies and activities to help students meet the learning goals of the NGSS. Teachers expressed that having opportunities throughout the workshop to learn from researchers and other teachers within and outside their school was invaluable, as they do not regularly have such opportunities. The final customized WISE units reflected the integration of the ideas and expertise of researchers and teachers. Thus, the workshop embedded research-based pedagogical insights into teachers' curriculum customization practices and expanded researchers' understanding of teachers' instructional constraints and resources.

Making thinking about customization visible

To customize the WISE units, we designed workshop activities that made the customization process visible. The diagrammed WISE units made the researchers' thinking visible to teachers by highlighting the units' salient features and the researchers' design rationale. The diagrammed units facilitated productive conversation about the feasibility of unit implementation and theories of learning, specifically the KI framework. Writing their ideas for lesson activities on sticky notes color-coded according to the steps of the KI process provided teachers tangible artifacts with which to organize their current curriculum materials in ways that would support constructivist-grounded pedagogy. Having the content of the sticky notes at the grain-size of lesson activity supported experimentation with lesson structure and sequence. Teachers could place and replace the notes on the lesson notecards. Thus, the customization activity helped participants make their thinking visible by moving their ideas from conceptualization to paper, making their ideas available for evaluation and revision by themselves and others. The activities also helped make learning the KI framework accessible to teachers, thereby providing teachers and researchers with a common pedagogical lens with which to evaluate and customize curriculum.

Supporting sustainable customization practices

After the workshop, teachers and researchers partnered to implement the customized WISE units. The two cases presented in this paper, highlight the power of the professional development activities to promote sustainable curriculum customization practices. In one case, the teacher (Mr. Vega) implemented a customized Photosynthesis WISE unit which he did not work on during the workshop. During implementation he applied the KI framework to effectively interleave his existing curriculum activities into the digital WISE Photosynthesis unit to support his primarily English Language Learner students in developing a coherent understanding of the targeted performance expectations. Similarly, the other teacher (Mr. Harrison) customized the WISE Photosynthesis unit to supplement his existing curriculum. He recognized that his existing curriculum did not support students to distinguish their ideas, a critical step in the KI process. He used WISE activities to do so. Both teachers noted that the structure of the WISE units, namely a series of related yet independent lessons targeted to specific NGSS performance expectations that engage students in each step of the KI process, made customization feasible and effective. Rather than viewing the WISE units as a product of research efforts that needed to remain unedited, both teachers viewed the units as their own and acted accordingly. The workshop developed teacher agency around curriculum customization thereby allowing the customized WISE unit to be the product of a partnership between education experts, experts of theory and experts of practice.

Make customization accessible

The diagrammed version of the WISE units and the workshop activities provided a prototype for an online customization and implementation interface. This interface makes the customization process accessible to teachers. Teachers commented that the diagrammed WISE unit provided the ideal amount and type of information they needed to gain a working knowledge of a unit. They also valued the intuitiveness of customizing units with activity-level sticky notes color-coded for the KI process. Using these experiences, the researchers and WISE technology team designed a customization and implementation interface on the WISE platform. When teachers view a WISE unit from the interface, they will see a pop-out window with the same information that was on the notecards. Upon selecting the unit for implementation, the unit will be displayed at the activity level with each activity tagged for the KI step that it targets. Teachers can add specific activities from other WISE units or from their own resources. In the future, we anticipate integrating with Google Classroom so that teachers can seamlessly combine their existing curriculum with WISE lessons or activities. Additional analysis of the final customized unit will help ensure that teachers have a customized curriculum that engages their students in compete KI cycles. The interface will allow teachers and researchers to continually benefit from each other's respective expertise and sustain their curriculum customization partnership.

Study 3 Conclusions

The outcomes and associated principles presented in this study illustrate the promise of the KI professional development activities to support the alignment of existing curriculum with NGSS. Analysis of the activities suggest three design principles that echo the KI tenets: learning from others, making thinking visible, making learning accessible, and promoting autonomous learning (Linn et al., 2011). The findings also illustrate the value of logging student activities and using student work to support customization. The findings, however, come with limitations, namely not evaluating the impact of the co-designed unit on student learning. There was also the limitation associated with implementing teachers' customization decisions into the WISE system, which due to system infrastructure constraints had to be done by the researchers and system developers. Consequently, there could have been misalignment between the intention and implementation of the unit customization. Work in underway to address this limitation, as we are developing a teacher customization interface in WISE to facilitate teacher-directed customization planning and implementation. Progress thus far is promising as evidence by observational and survey data from teachers at a customization workshop (data unpublished).

Chapter 3 Summary

The RPP-based approach for curriculum development was an effective approach for redesigning the WISE Photosynthesis unit to further support students in developing an integrated understanding of energy and matter transformation during photosynthesis. Through this partnership, teachers co-designed the new WISE Photosynthesis unit by strategically interleaving their own curriculum activities into the unit lessons. A comparison of the photosynthesis unit before and after co-designing can be found in Appendix B.

The results of Study 3 suggest that while teacher-derived activities supported most of the KI process, teachers relied upon researcher-designed models and simulations to facilitate students' engagement in the complete KI process. If teachers rely on WISE-based activities to assist them in supporting their students to engage in the full KI process, then they need to be informed about their students' progress toward developing integrated, three-dimensional knowledge while learning with WISE. Learning analytics can help meet this need.

I argue that incorporating learning analytics targeted to key elements in the WISE photosynthesis units could allow teachers to use evidence of student learning in real-time to make targeted curriculum customizations, such as interleaving their own activities. In chapter 4, I describe the strategy I used to design the learning analytics and teacher dashboard for the co-designed WISE Photosynthesis unit.

CHAPTER 4 - STRATEGIES FOR DESIGNING LEARNING ANALYTICS AND A TEACHER DASHBOARD TO PROMOTE KNOWLEDGE INTEGRATION

Chapter 4 Overview

The central purpose of learning analytics (LA) is to support: the understanding of learning; the optimization of the learning environment; and evidence-based pedagogical action (Ferguson, 2012). While many design efforts have attended to certain aspects of this purpose, few have been successful at attending to all aspects (Mangaroska & Giannakos, 2018). In their recent systematic literature review of LA for Learning Design studies, Mangaroska and Giannakos (Mangaroska & Giannakos, 2018) identify numerous factors that limit the effectiveness of LA, including the lack of grounding in a theory of learning, and the lack of alignment with a theory-grounded learning design. I claim that in order for LA to be effective for classroom learning, the development strategy needs to attend to all three aspects of the purpose. In this chapter, I describe such an LA development strategy and how I implemented it to develop LA for the co-designed WISE Photosynthesis unit.

STUDY 4 - DEVELOPING A STRATEGY FOR DEVELOPING AND IMPLEMENTING LA FOR INTEGRATED, THREE-DIMENSIONAL KNOWLEDGE OF PHOTOSYNTHESIS

Despite its great potential, the hope for LA to improve teaching and learning has not yet been fully realized (Wise & Vytasek, 2017). Some researchers attribute the unrealized potential of LA to a misalignment in the learning design and the analytics (Lockyer et al., 2013), others to the absence of a grounding theory of learning (Wise & Schaffer, 2015), and still others to the absence of teacher involvement in the design of the analytics (Prieto et al., 2018) The strategies presented in this study address each of these issues.

Background

Grounding LA in a theory of learning

Gašević and colleagues (2017) identify theory—along with design and data science—as a key dimension of LA. While many studies attend to the dimensions of design and data science, greater attention needs to be given to theory since it is theory that differentiates LA from data analytics (Reimann, 2016). Grounding LA in theory can prevent haphazard data selection during LA development which often biases towards data that are simply proximal to rather than consequential for learning (Reimann, 2016).

When grounded in theory, LA can function as a methodology for learning science research and, thereby, fulfill its purpose of supporting an understanding of learning (Reimann, 2016). Bergner and colleagues (2018) note that methodologies are positioned at the intersection of the "what" and the "how". Consequently, using LA as a methodology helps to interrogate what is being studied (i.e. learning) and how it is being studied (i.e. through the learning design). It is the theory dimension of learning theory that is essential for its function as a methodology as theory informs the decision of which data are most appropriate for measuring a particular aspect of learning. Theory also facilitates the explanation of analytics-identified student outcomes and lights the path for responsive action (Reimann, 2016). Thus, if LA are to be used as a methodological tool for classroom learning, greater focus on learning theory must be placed during LA development.

Aligning to theory-grounded learning design

The learning that takes place in a classroom can be designed for. As the name suggests, a learning design is the design for a desired type of learning. Goodyear and Dimitriadis (2013) identify the aspects of learning that can be designed for: the most appropriate student grouping; the tasks to be performed; and the physical and digital environment (i.e. the learning resources, artifacts, and activities). Asensio-Pérez and colleagues (2017) describe learning design development as a 3-phase cycle consisting in rounds of creation, orchestration, and assessment (Figure 9). The cycle begins with the creation of specific tasks, intended social structures, artifacts, and resources to facilitate the desired learning. During the orchestration (i.e. implementation) phase, the learners' engagement with these elements is monitored, regulated, and scaffolded with the goal of supporting the desired learning. Learners' artifacts are then assessed to determine how the learning design can be redesigned or re-instituted to achieve the desired learning.

Given its focus on designing the path for learning, a learning design is an intuitive partner for LA. Numerous studies highlight the importance and value of the alignment between LA and the learning design (Mangaroska & Giannakos, 2018; Persico & Pozzi, 2015). When LA are aligned to the learning design cycle, they can provide teachers with actionable insight to optimize the learning design and therefore, support student learning (Hernández-Leo et al., 2019). In the following section I describe how this alignment can be achieved.

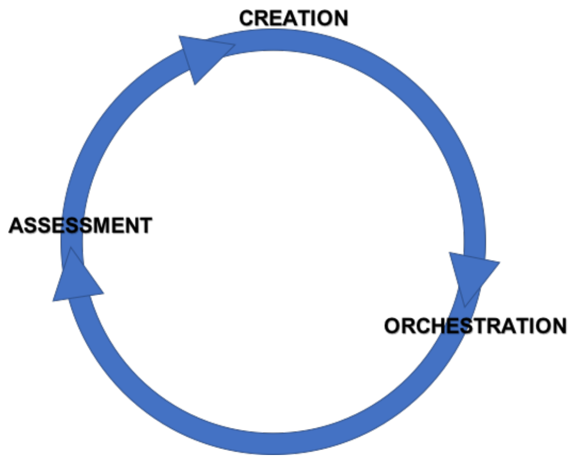


Figure 9: The three phases of the learning design cycle: creation, orchestration, and assessment

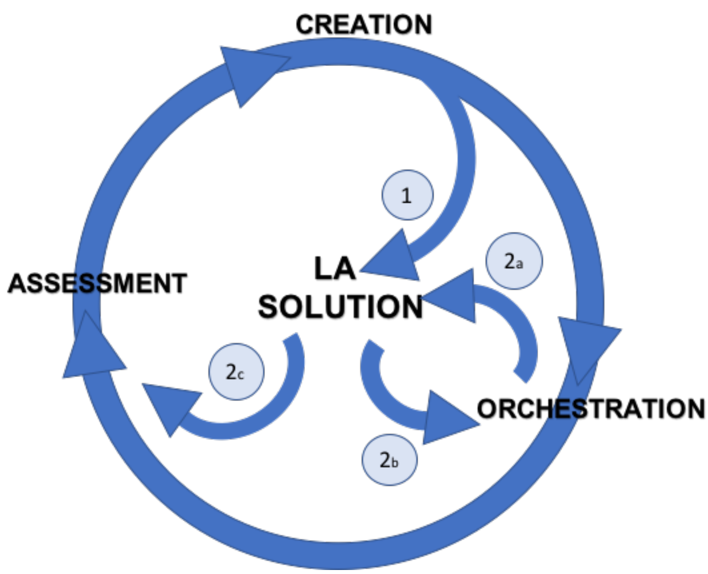


Figure 10: The integration of LA development into the learning design cycle. 1 – LA design: learning design elements selected as targets for LA; 2 – LA implementation: a.) data from LA targets is analyzed by the LA tool, and the resulting LA informs: b.) orchestration, c.) and assessment

To illustrate, after the learning design is created, specific elements of the design are identified as data sources for the LA (Figure 10, 1). During the orchestration phase, the LA are implemented, and the selected LA targets generate data for analysis (Figure 10, 2a). The resulting LA can then support the understanding of the learning taking place and inform about which pedagogical interventions and orchestration actions are needed to optimize that learning process (Figure 10, 2b). The LA can also support the assessment phase of the learning design cycle, by providing insight into the effectiveness of the targeted elements in facilitating the desired learning outcomes (Figure 10, 2c).

Grounding LA and learning design in the same theory of learning is critical to their ability to support the optimization of the learning design (Gašević et al., 2017; van Leeuwen, 2015; Lockyer et al., 2013). Lockyer et al. (2013) argue that theory-grounded learning design documents the pedagogical intent and provides an interpretative lens for making sense of LA. They further contend that theory-grounded learning design supports pedagogical action by conveying expected student outcomes against which actual outcomes, as represented in the LA, can be compared. It is the theory component of LA that creates these affordances (Reimann, 2016). By virtue of their common theoretical grounding, discrepancies between expected learning outcomes and actual outcomes provide a clear signal for where and how to customize the learning design. (Lockyer et al., 2013; Wise & Vytasek, 2017).

Research Question

In this study, I address the following research question: How can LA and a teacher dashboard be created to provide teachers with actionable insight for supporting integrated, three-dimensional knowledge?

Specifically, I describe a strategy for creating LA and an associated teacher dashboard that can function methodologically to provide insight into: (a) how students are integrating their ideas about energy and matter transformation during photosynthesis, and (b) how to optimize the design for this learning.

RQa - Creating theory-grounded learning analytics to assess knowledge integration

Developing and Evaluating LA for integrated, three-dimensional knowledge

To assist teachers in supporting students to develop an integrated understanding of energy and matter transformation during photosynthesis, I created LA aligned to the co-designed WISE Photosynthesis unit. In a KI-based learning design, students' integrated understanding is demonstrated on items aligned to the connecting ideas step of the KI process. However, the NGSS guidelines for assessment development (Achieve, 2018) calls for assessment that require students to demonstrate all three dimensions. In other words, one assessment needs to target all three of the dimensions included in the PE. Therefore, the assessment item that I chose to be the LA target was the connecting ideas item, "Cow Energy Story" (Figure 11), which was a variation of the "Energy Story" item used in Study 2. This item also aligns with the NGSS performance expectation, MS-LS1-6 requires students to

> "Construct a scientific explanation based on evidence for the role of photosynthesis in the cycling of matter and flow of energy into and out of organisms" (NGSS, 2013).

Building a Reliable and Valid Rubric for three-dimensional knowledge. The NGSS performance expectations require students to develop three-dimensional knowledge. Accordingly, the NGSS performance expectations are written to reflect the integration all three dimensions such

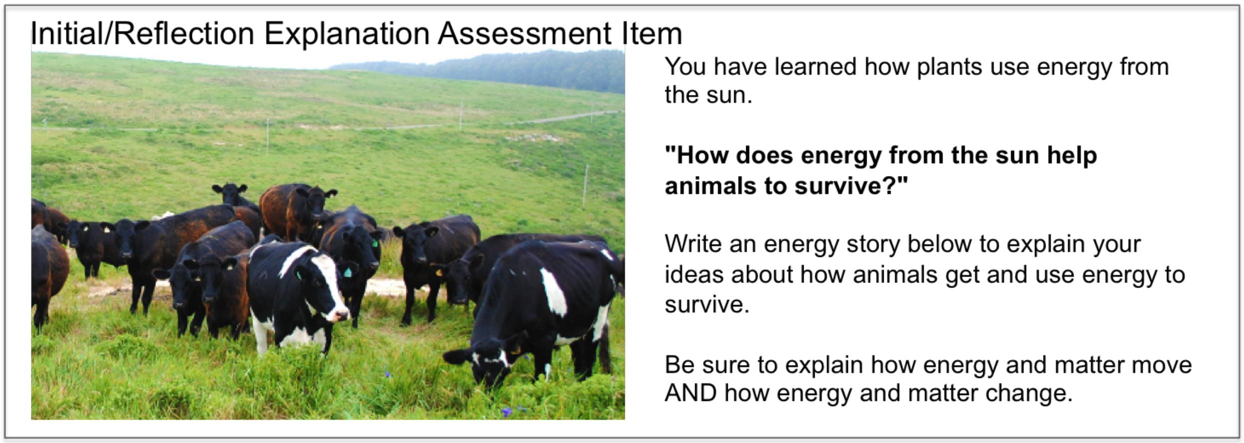


Figure 11: Prompt for the Initial/Reflection Explanation item Note: The Reflection Explanation item prompt had the statement "Revise your energy story to explain your new ideas about how animals get and use energy to survive."

that students use a Science Engineering Practice (SEP) to demonstrate integrated understanding of the Disciplinary Core Idea (DCI) and Crosscutting Concept (CCC). For MS-LS1-6, the three-dimensional breakdown is as follows:

- "Construct a scientific explanation based on evidence for..." (SEP)
- "...the role of photosynthesis in the cycling of matter and flow of energy into and out of organisms" (DCI)
- "...the cycling of matter and flow of energy..." (CCC)

Developing SEP Criteria. Since three-dimensional knowledge is a form of knowledge integrate, my method for assessing students' progress in developing integrated, three dimensional knowledge, began by transforming the KI rubric created in Study 2 into an NGSS performance expectation (PE) rubric (Figure 12). KI rubrics have been well established as effective tools for assessing integrated understanding (Liu et al., 2016). This particular KI rubric was a logical starting point since students must integrate normative science ideas to effectively engage in the practice of constructing a scientific explanation. Therefore, I used the criteria from the KI rubric in Study 2, which measured the construct of integrating normative science ideas on a 1-5 scale, to measure the SEP construct, constructing a scientific explanation.

Developing DCI and CCC Criteria. To develop the criteria for the DCI and CCC dimensions, I drew upon the NGSS Evidence Statement for MS-LS1-6 (Achieve, 2013). These documents, which teachers confirmed in the workshop described in Study 3 (unpublished data) function as a guide for assessing student learning artifacts. They describe the "observable features" that should be evident in student learning artifacts. Additionally, the evidence statements detail the specific pieces of evidence from the targeted phenomenon. These pieces of evidence articulate the normative science ideas for the DCI and CCC. The evidence statements also describe the "reasoning"

Coherence Score Description	**Score Level**	**Idea Score Description**
Off-task response	1	No discussion of target ideas
No link - Alternative or invalid ideas	2	Partial discussion of target ideas
Partial link - Normative ideas without any scientifically valid links between normative ideas	3	Full discussion of target ideas
Full link - One scientifically valid links between normative ideas	4	
Complex link - Two scientifically valid links between normative ideas	5	
Scientifically Valid Link Description		**Photosynthesis & Producer/Consumer Relationships (DCI)**
Energy transformation: One type of energy can be transformed into another type of energy. Light energy is transformed into chemical energy during photosynthesis.		Idea #1: Full = CO_2 + H_2O --> (via arrangement or chemical reaction) glucose + oxygen, uses energy from sun/light to do photosynthesis reaction Not good enough for partial credit to just say that the plant gets/uses energy from the sun to grow, need to say or describe photosynthesis
Matter transformation: Reactants, such as carbon dioxide and water, are transformed into products, glucose and oxygen.		Idea #2: Full = Explicit statement about what specifically the PLANT uses glucose/food (not CO_2, H_2O, light) for: growth, energy, stored, repair, seed production
Energy–matter relationship: Energy is required to initiate a chemical reaction (bond breaking). Chemical energy is stored in glucose (matter).		
		Energy Transfer Drives Matter Cycling (CCC)
		Idea #1: Full = Energy (any type of relevant energy) and matter (any type of relevant matter) moves WITHIN THE PLANT during photosynthesis
		Idea #2: Full = Energy from the sun gets to animals when they eat photosynthetic plants, directly or indirectly. (i.e. when animals EAT plants or plant-eating animals breathe in oxygen for food/energy)

Figure 12: Rubric used for scoring the assessment items.

that should be evident in students' learning artifacts. The reasoning represents how students are expected to integrate the DCI and CCC pieces of evidence, respectively. In this way, the DCI related reasoning statements reflect integrated DCI ideas, and the CCC reasoning statements reflect integrated CCC ideas. As such, these reasoning statements were used to develop the highest rubric criteria level (level 3) for the DCI and CCC dimensions, respectively. The other levels for the DCI and CCC criteria of the PE rubric reflected the extent to which the DCI and CCC ideas were present, either partially (level 2) or not at all (level 1). Since the performance expectation represents the desired integration of the DCI ideas and CCC ideas, the scores associated with the individual rubric criteria were termed, subscores. Connecting back to the dimensional breakdown, the DCI and CCC subscores reflected the extent to which students understood the details of photosynthesis, and its role in the cycling of matter and flow of energy, respectively.

Reliability Testing. To test the reliability of the PE rubric for MS-LS1-6, I exported from the WISE system 500 written responses to the Cow Energy Story item from previous implementations of the co-designed WISE photosynthesis unit. The responses came from anonymized students in the classrooms of nine Bay Area middle school science teachers spanning four schools in four districts. The responses were coded by two researchers using the PE rubric and following the method describe by Liu et al. (2016). Specifically, each coder individually scored 10% of the responses, then resolved any scoring discrepancies through discussion. Once the inter-rater reliability, as determined by Cohen's Kappa, reached 0.90 or greater, the remainder of the responses were scored by a single coder.

To facilitate real-time availability of the LA, the 553 human-scored responses were used to train a neural network (i.e. machine learning) model for the DCI and CCC dimensions that could automatically score students' responses immediately after submission on the WISE platform. The model training yielded a human-computer inter-rater reliability slightly less than human-human scoring (quadratic weighted kappa: DCI = 0.707; CCC = 0.683) but still acceptable (Riordan et al., 2020; Fleiss et al., 2003). A model was also developed for the SEP/KI dimension using 1,411 student responses, reflecting the combined total of the responses used for DCI and CCC model training and prior years training efforts). This model was similarly evaluated for reliability (SEP/KI quadratic weighted kappa = 0.825) (Riordan et al., 2020).

Validity Testing. Since LA can only support learning to the extent that the data upon which they are based reflect the learning process (Reimann, 2016), I conducted validation tests to evaluate whether the PE rubric criteria for the DCI and CCC dimensions were distinct. In other words, I wanted to verify that the data upon which the LA were based (i.e. the subscores) truly reflected students understanding of the details of photosynthesis, and its role in the cycling of matter and flow of energy (i.e. the DCI and CCC, respectively). Having already confirmed the reliability of the scoring criteria, I used the same 500 scored responses for the validation tests, following the procedure detail by Watson and Petrie (Watson & Petrie, 2010).

The first validation test that I conducted was a correlation analysis. Given that DCI and CCC reflect related but distinct ideas, I would expect a moderate Spearman's rho, which is what I found ($r = 0.57$, $p < 0.001$). Exploration of the relative distribution of scores using cross-tabulation analysis revealed distinct yet overlapping populations (Figure 13). For the cross-tabulation analysis, the criteria levels for each dimension were collapsed, generating binary variables that represented the presence of the fully integrated ideas (value = 1) or not fully integrated ideas (value = 0). The distribution pattern associated with these binary variables for the DCI and CCC dimensions indicates a significant proportion of scores that do not overlap (i.e. a substantial off-diagonal distribution). This pattern is consistent with their conceptual relationship, namely that they are conceptually related yet distinct ideas.

To further explore the relatedness between the DCI and CCC constructs, I calculated the positive predictive value using the scores for each dimension. While the positive predictive value of

$\chi^2(1) = 103.84$ $p_{exact} < 0.001$	CCC Ideas		
DCI Ideas	Not Fully Present	Fully Present	Total
Not Fully Present	303 (61%)	131 (26%)	434 (87%)
Fully Present	10 (2%)	56 (11%)	66 (13%)
Total	313 (63%)	187 (37%)	500 (100%)

Figure 13: Frequency of scores reflecting the presence or absence of fully integrated DCI and CCC ideas. McNemar's Chi-squared and exact significance probability are included.

the DCI criteria for the CCC construct was 85%, the positive predictive value of the CCC criteria for the DCI construct was 30%. These results suggest that the DCI score is a better predictor of the CCC score than vice versa. That the DCI score is a good predictor of the CCC score aligns with the Study 2 result (ref. Chapter 2 Figure 7) which indicated that developing a mechanistic understanding of photosynthesis, corresponding to fully integrated DCI ideas, can explain students' be able to demonstrate an understanding of the role of photosynthesis in the cycling of matter and flow of energy, which corresponds to fully integrated CCC ideas.

To further explore the construct validity of the DCI and CCC criteria, I conducted a test for inter-rater reliability, treating the criteria for measuring the DCI and CCC as two methods of measurement. My null hypothesis was that the DCI and CCC criteria represent two methods for measuring the same construct, and as such would generate a weighted kappa statistic greater than 0.60. However, if the two criteria measure different constructs, as designed, then conducting an inter-rater reliability on the scores of the same response using the two criteria would yield a weighted kappa statistic less than 0.40, which is what I found (weighted kappa = 0.278). The findings from the validation tests indicate that the DCI and CCC rubric criteria have both psychometric and theoretical validity. Thus, by drawing on the reasoning statements which provide explicit expressions of the ideas that students need to develop and what an integration of those looks likes, I was able to develop a reliable and valid rubric for measuring students' progress along these two dimensions.

Taken together with the previously demonstrated reliability and validity of the SEP/KI rubric criteria, these results affirm the use of the 3-in-1 PE rubric as a measurement tool for assessing both knowledge integration and the three-dimensional learning called for by the NGSS. Furthermore, these results provide confidence that the LA developed from these rubric scores reflect the designed for learning. Consequently, the LA can function as a methodology for helping teachers (and researchers) understanding how students are integrating their ideas about energy and matter transformation during photosynthesis and how to optimize the design for this learning.

Nevertheless, to provide teachers with more robust insight for supporting students in developing integrated, three-dimensional knowledge (Fuchs & Diamantopoulos, 2009), future research should apply this 3-in-1 rubric strategy to multiple assessment items that are aligned to a target PE. In this way, teachers can have a better understanding of students' learning needs and thus develop more effective instructional interventions.

The combined results from the studies present thus far point to the value of providing teachers with LA about their students' progress toward developing integrated ideas about the complex process of photosynthesis. Armed with these LA, teachers could understand their students' learning needs and make customizations to the learning design to support student learning.

In the next section, I describe the design of an interpretable and actionable LA dashboard. I also describe how I implemented the KI- and NGSS-aligned LA into this dashboard to provide teachers with real-time pedagogical assistance for supporting students in developing integrated, three-dimensional knowledge of energy and matter transformation during photosynthesis.

RQb - Designing A Teacher Dashboard to support knowledge integration

LA dashboards have emerged as a way to provide teachers with real-time pedagogical support. Interpretability and actionability have been identified as critical factors in the developing LA dashboards that support teachers in taking LA-informed pedagogical action (Clow, 2012; Jørnø & Gynther, 2018; Wise et al., 2016; Alhadad, 2018). Implementing data visualization design principles during the LA development is an effective strategy for supporting LA interpretation (Alhadad, 2018; Echeverria, Martinez-Maldonado, et al., 2018). However, Echeverria et al. (2018) argue that to make an LA dashboard actionable for teachers, not only does it need to be aligned to a theory-grounded learning design but teachers need to understand the alignment. Specifically, an LA dashboard needs to present data directly related to the educational objectives. Echeverria et al. (2018) propose using an "educational data storytelling" (EDS) approach to develop such dashboards.

The EDS approach calls for the alignment of LA data with the learning design and the implementation of data visualization principles (Echeverria, Martinez-Maldonado, et al., 2018; Alhadad, 2018). The goal of the EDS approach is to create an LA dashboard that provides teachers with insight into student engagement with the learning design (ref. Figure 10, 2b). To design the LA teacher dashboard for the co-designed WISE Photosynthesis unit, referred to as the Teacher Action Planner (TAP), I drew upon the following six EDS principles:

- EDS Principle 1: Align the LA dashboard with a clear educational goal derived from the learning design
- EDS Principle 2: Choose appropriate visual to effectively communicate the desired message to the target audience
- EDS Principle 3: Use narrative text to summarize visual features and create meaning
- EDS Principle 4: Use visual elements (e.g. lines, weight, colors, contrast, alignment) to direct visual attention and enhance sense making
- EDS Principle 5: Use titles and captions to communicate the intent of the visual elements and explain relevant features in the data

- EDS Principle 6: Maximize the data-ink ratio by excluding unnecessary headers, chart features, borders, grids.

TAP Dashboard Development

I designed the TAP in collaboration with the WISE system developers to provide teachers with information regarding student performance on an assessment item that prompts students to write an explanation of the role of photosynthesis in the cycling of matter and flow of energy 11. I implemented the six EDS principles (indicated with red circled numbers in Figure 14) as follows.

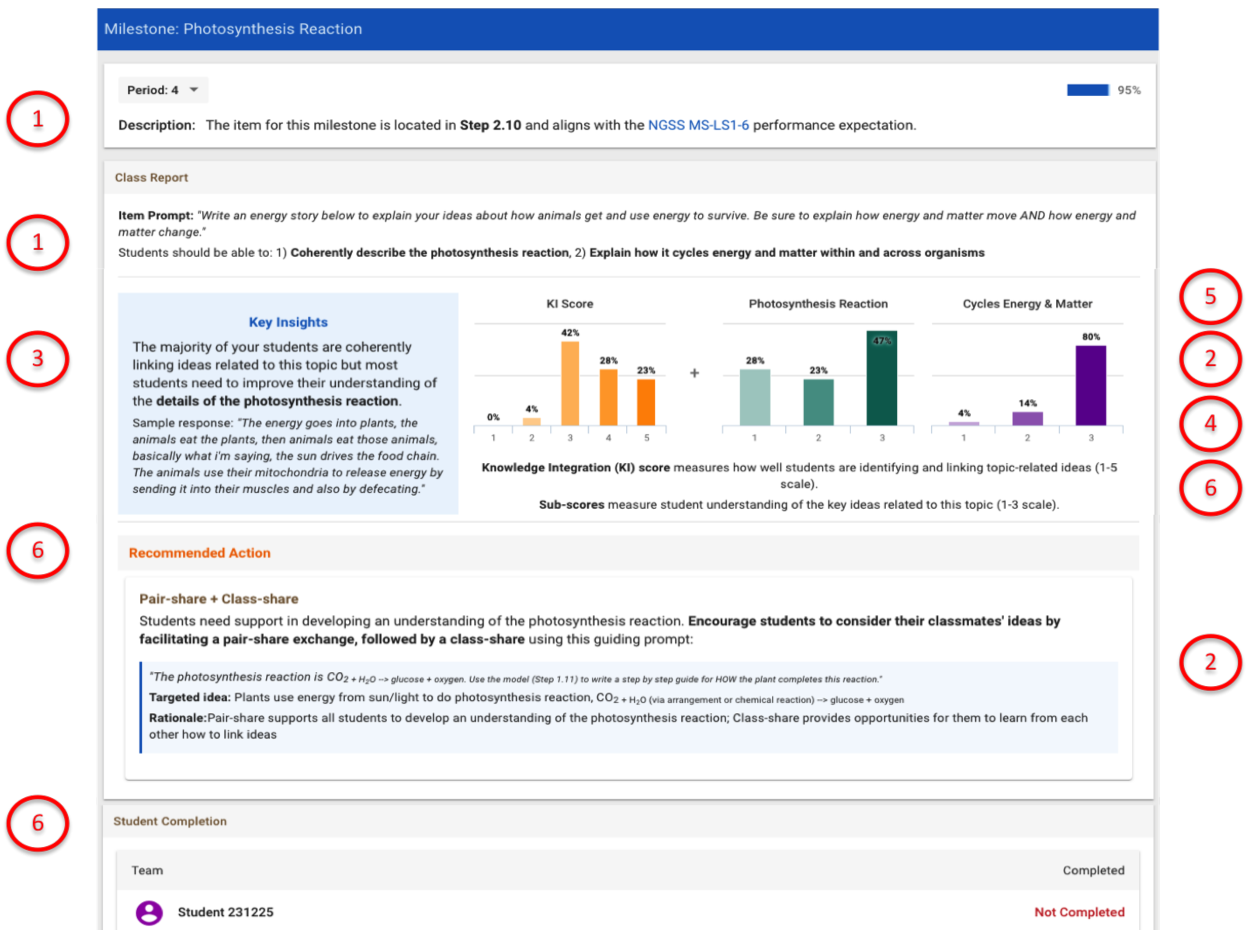


Figure 14: Annotated TAP Displays. Red, circled numbers indicate the implementation of the correspondingly numbered Educational Data Storytelling Principle.

EDS Principle 1: Align the LA dashboard with a clear educational goal derived from the learning design. We aligned the TAP to the middle school life science NGSS performance expectation, MS-LS1-6. This performance expectation calls for students to demonstrate an integrated understanding of energy and matter transformation by constructing a scientific explanation of the role of photosynthesis in the cycling of matter and the flow of energy. It was articulated in numerous ways at the top of the dashboard. We included a link to the webpage detailing the NGSS performance expectations in the description of the assessment item and the item's location in the photosynthesis unit. We also provided the exact prompt for the assessment item and summarized the lesson's learning objective to link the language used in the performance expectation with the language used in the item prompt.

EDS Principle 2: Choose appropriate visual to effectively communicate the desired message to the target audience. Anonymized student responses to the assessment items (Figure 11) were autoscored using proprietary algorithms developed with our collaborators to generate scores for students' progress along each NGSS dimension (Authors, 2019). The DCI and CCC scores (scale 1-3) reflected the extent to which students express targeted DCI and CCC ideas, as described in the MS-LS1-6 Evidence Statement (Achieve, 2013; Figure 12). Since the SEP for MS-LS1-6 is to construct an evidence-based explanation, students' progress along this dimension was reflected in their KI score (scale 1-5). The KI score was based on the KI rubric used in Study 2, which prioritizes the links students make between normative ideas about photosynthesis (ref. Chapter 2 Table 3).

The LA for students' performance on the embedded assessment item was aggregated by class period and reported using bar graphs as the percentage of students scoring at each score level for each dimension score. We represented the LA using bar graphs given teachers' likely familiarity with this data format (Alverson & Yamamoto, 2016; Whitaker & Jacobbe, 2017). Using bar graphs also seemed the most appropriate data format given our desire for teachers to compare the percentage of students across the different score levels.

EDS Principle 3: Use narrative text to summarize visual features and create meaning. Next to the graphs, we included a summary of the LA, called Key Insights, which represented the key message that we wanted teachers to get from the LA. The narrative described students' performance along two parameters, whether they expressed the targeted ideas (DCI ideas and CCC ideas) and whether those ideas were coherently linked. The narrative was written as a call to action for teachers to support students in the identified area of need.

EDS Principle 4: Use visual elements to direct visual attention and enhance sense making. To support teachers in quickly understanding the LA data, we added data labels and major gridlines to the bar graphs. The data labels provided teachers with specific percentages to take note of and the major gridlines would support teachers to make comparisons across score levels. We also emboldened certain words and phrases in the dashboard to draw teachers' attention to important aspects of the information being presented, such as the target learning objective, and the portion of the Key Insights that identified the target ideas for which students needed the greatest support to understand.

EDS Principle 5: Use titles and captions to communicate the intent of the visual elements and explain relevant features in the data. We used the assessment item topic for the title of the LA dashboard (e.g. Milestone: Photosynthesis Reaction), and for each section of the dashboard, we included a short descriptive title (e.g. Class Report, Recommended Action). We captioned the graphs with the name and brief description of the scores being presented.

EDS Principle 6: Maximize the data-ink ratio by excluding unnecessary headers, chart features, borders, grids. Given our inclusion of data labels for the bar graph, we eliminated the y-axis line, deeming it redundant and unnecessary. We also chose not to have borders for the graphs.

TAP Recommended Actions

To support teachers in making evidence-based customizations to the learning design, a recommended action was created for each possible data scenario across the three scoring dimensions (i.e. SEP/KI, DCI, and CCC). We created binary score categories for each dimension: High/Low KI: above/below score 3, respectively; Full/Not Full DCI: above/below score 3, respectively; Full/Not Full CCC: above/below score 3, respectively. Although there is a total of eight possible data scenarios, the scenario of high scores across all three dimensions was excluded since this represented the ideal learning outcome and thus not warrant a modification of the learning design. The decision to create binary score categories was substantiated by the distribution pattern associated with the DCI and CCC scores, namely that the categorization based on the presence or absence of fully integrated DCI/CCC ideas produces statistically significant population distinctions.

The recommended actions were designed to engage students in the full process of knowledge integration according to the KI framework (Figure 15). The activity structures for the instructional interventions were based on learning science research and my 10+ years of experience teaching the topic at the middle and secondary level. To support teachers in understanding the recommended action and encourage them to implement it, we included a statement of rationale. The rationale informed teachers of the pedagogical reasoning for and intended outcome of having their students engage in the intervention. These recommended intervention activities make the TAP actionable, effectively "closing the loop" of the learning analytics cycle (Clow, 2012; ref. Figure 10).

Recommended Action

Pair-share + Class-share

Students need support in understanding and linking the details of the photosynthesis reaction. **Encourage students to consider their classmates' ideas by facilitating a pair-share exchange, followed by a class-share** using this guiding prompt:

> *"Use evidence from the model (Step 1.11) to describe exactly how energy from the sun ends up in the glucose that plants make during photosynthesis"*
>
> **Targeted idea:** Plants use energy from sun/light to do photosynthesis reaction, CO_2sub> + H_{20} (via arrangement or chemical reaction) --> glucose + oxygen
>
> **Rationale:**Pair-share supports all students to use their understanding of the how photosynthesis cycles energy and matter to develop an understanding of the details of the photosynthesis reaction; Class-share provides opportunities for them to learn from each other how to link ideas

Knowledge Integration Process	Recommended Action #1 (above)	Recommended Action #2 (below)
Elicit Ideas	Sharing with partner	Looking for evidence in the model
Add Ideas	Exploring model	Reading peers responses
Distinguish Ideas	Using evidence to describe how glucose gets energy from the sun	Determining whether to support, refute, or clarify their peers ideas
Connect Ideas	Class discussion facilitates synthesis of ideas	Using evidence to support, refute, or clarify their peers ideas

Recommended Action

Jigsaw based on KI score

Students need support in both developing and linking their ideas about this topic. **Have students engage in a jigsaw discussion activity, pairing up teams that have different KI scores.** Use this guiding prompt:

> *"Find evidence in the model (Step 1.11) to either support, refute, or clarify the claims made in this response (use responses from each KI level)."*
>
> **Targeted ideas:** 1) Plants use energy from sun/light to do photosynthesis reaction, CO_2sub> + H_{20} (via arrangement or chemical reaction) --> glucose + oxygen, 2) Energy from the sun gets to animals when they eat photosynthetic plants
>
> **Rationale:** Jigsawing based on KI score allows students to develop the particular skill they need (1/2: gather ideas to support claim, 3: gather evidence to refute claim, 4/5: identify ways to clarify claims). The mixed groups encourages all students to learn from each other either new ideas, how to coherently link ideas, or how to clarify/elaborate ideas.

Figure 15: The Recommended Actions that teachers received in the TAP (top, bottom) and how each action aligned with the steps of the Knowledge Integration process.

Study 4 Conclusions

The results of the PE rubric evaluation suggest that the multi-dimensional rubric is both reliable and valid for each construct being measured (i.e. the three dimensions of the NGSS). The results thus affirm the approach taken to develop the PE rubric and demonstrate its viability as a general method to apply to other NGSS performance expectations or other standards-based learning goal.

Although validation conventions in the field of psychometrics call for the use of multiple items to measure multi-dimensional constructs like integrated knowledge (Fuchs & Diamantopoulos, 2009), since the DCI and CCC dimensions for any given performance expectation reflect specific ideas, they generate an extremely small sample space. Consequently, using a single-item assessment strategy may not be problematic.

The lack of direct teacher involvement in the design of the TAP interface has the potential to limit its success in supporting classroom instruction. This study, however, represents the first or many future design iterations, which will draw on the expertise of all stakeholders, including teachers and students.

Chapter 4 Summary

In this chapter, I described a research-based strategy for developing effective LA using learning-congruent data (i.e. data that align and reflect with students' engagement in the learning process). Specifically, I described how the theory-grounded KI framework served as the basis for selecting and analyzing student response data associated with targeted assessment items in the co-designed WISE Photosynthesis unit. I also described the development and evaluation of a rubric designed to assess each dimension of the NGSS performance expectation being targeted by the assessment items, called the PE rubric.

I also described my implementation of the Educational Datastorytelling Principles, to create a teacher LA dashboard, called the TAP. The TAP displayed LA based on the evaluation of student scores using the PE rubric to support teachers in understanding their students' progress in developing integrated, three-dimensional knowledge of energy and matter transformation in photosynthesis. The TAP was also designed to support teaching in making evidence-based customizations to the learning design and taking pedagogical actions to support student learning.

In chapter 5, I describe a classroom study in which I evaluate the ability of the TAP to support student learning during a classroom implementation of the co-designed WISE Photosynthesis unit.

CHAPTER 5 - A TEACHER DASHBOARD FOR SUPPORTING KNOWLEDGE INTEGRATION

Chapter 5 Overview

The increased use of technology enhanced learning (TEL) environments, particularly in science classrooms, has helped to transform teachers from information givers to learning facilitators (de Jong, 2019). As learning facilitators, teachers need information about students' struggles and successes during the learning process. Coffey and Hammer (2011) and Bang and Marin (Bang & Marin, 2015) demonstrated the effect that teachers' attention to their students' ideas has on learning. Relatedly, Robertson, Scherr, and Hammer (Robertson et al., 2016) note that students' ability to develop an integrated understanding of complex phenomena, like photosynthesis, is related to their teachers' ability to notice and respond to their developing ideas. However, the numerous factors and constraints during classroom instruction that teachers have to negotiate create barriers for attending to student ideas. Supporting all types of teachers to engage in formative assessment of student thinking is an active research issue. Some researchers use educative curriculum materials (Roseman et al., 2017; Krajcik & Delen, 2017), professional development (Otero, 2006; Leary et al., 2016), instructional technology (Gerard & Linn, 2016; Walkoe et al., 2017), or learning analytics dashboards (Mor et al., 2015; van Leeuwen, 2015). I adopted the latter approach.

Technology-enhanced learning environments implemented in science classrooms, like WISE, generate a wealth of data that can be transformed into learning-congruent data. When teachers receive, understand, and act on learning-congruent data they can support student learning (Rodríguez-Triana et al., 2015). Learning analytics (LA) dashboards have emerged as a means of representing and displaying learning data for teachers. Therefore, LA dashboards that provide teachers with learning-congruent data at key points during instruction can support teacher inquiry into student learning and inform pedagogical action (Lockyer et al., 2013; Mor et al., 2015; Rodríguez-Triana et al., 2015). An open question is whether LA dashboards support teachers to take actions that improve student learning. The study described in this chapter explores this question.

STUDY 5 - EVALUATING THE STUDENT LEARNING IMPACT OF A LEARNING ANALYTICS DASHBOARD IN A CO-DESIGNED PHOTOSYNTHESIS UNIT

Introduction

There is a growing awareness in the learning analytics (LA) field of the need to develop LA dashboards that are both interpretable and actionable. While the use of data visualization principles, based on research in the information and cognitive science fields, has successfully addressed the issue of interpretability (Alhadad, 2018), developing LA dashboards that support pedagogical action, and more specifically, action that improves student learning remains a research priority.

Researchers have taken numerous approaches to address this issue. Rodriguez-Triana et al. (Rodríguez-Triana et al., 2015) argue that in order for teachers to take action, they need explicit guidance not only for how to interpret and reflect on LA also, but also how to use it. Research in the area of classroom orchestration (i.e. implementing the learning design) has led to the development of pedagogical scripts to provide teachers with such guidance (Tissenbaum et al., 2012). Pedagogical scripts are designed in accordance with a theory of learning and reflect the mechanism by which learning is theorized to happen (Fischer et al., 2013). They apply to a specific learning scenario and identify the sequence and timing of learning activities, each learners' role, and how to manage particular interactions (Fischer et al., 2013). From a classroom orchestration perspective, teachers are the script managers and have the task of modifying the script to optimize student learning. Rodriguez-Triana et al. (2015) showed that when pedagogical scripts are embedded into a TEL environment, they are effective tools for supporting teachers in taking pedagogical actions.

Other researchers take a different approach towards supporting teachers in taking LA-informed pedagogical action. For example, Echeverria et al. (2018) developed the Educational Data Storytelling (EDS) approach which brings teachers "in the loop" during the LA development process (Rodríguez-Triana, Prieto, Martínez-Monés, et al., 2018). Using data visualization principles to align LA with teacher-specified learning objectives, Echeverria et al. (2018) developed what they called "explanatory learning analytics". In contrast to traditional analytics, which allow teachers to freely explore and interpret the data, explanatory analytics focus on one learning objective to communicate a specific message regarding students' performance. Echeverria et al. (2018) demonstrated that the Educational Data Storytelling approach produces LA that provide teachers with the level of understanding they need in order to take action.

In this study, we[3] evaluate a LA dashboard, called the Teacher Action Planner (TAP), that we developed in accordance with EDS principles, with certain features drawing upon the concept of pedagogical scripting. The TAP was embedded in the Web-based Inquiry Science Environment (WISE) system and provided teachers with LA regarding student learning with the co-designed WISE Photosynthesis unit. The learning design for the unit was developed according to the Knowledge Integration (KI) framework. As such, it elishortshortcited student ideas from their own experiences; engaged them in discovering new ideas using embedded models and simulations and hands-on activities; encouraged them to distinguish among their developing ideas; and provided them with opportunities to connect and reflect on their relevant ideas. The metric of learning for

[3] I switched to the first-person plural here and throughout the remainder of this chapter, excluding the Chapter Summary, as an acknowledgement of the collaborations that informed the studies presented herein, namely Yannis Dimitriadis and Marcia Linn.

this KI-based photosynthesis unit is students' integrated understanding of energy and matter transformation during photosynthesis and cellular respiration. The TAP was designed (ref. Chapter 4) to provide teachers with an analysis summary of students' scored responses to a unit-embedded assessment item targeting the performance expectation for middle school life science in the Next Generation Science Standards on photosynthesis (i.e. MS-LS1-6). Accordingly, the TAP also provided teachers with recommendations for pedagogical actions (i.e. less scripted versions of pedagogical scripts) that they could take to address the particular needs revealed by the analysis. We conjecture that using EDS principles to design an LA dashboard aligned to key elements of a KI-based learning design will support teachers to understand student learning and to optimize the learning design towards improved learning outcomes.

In the remaining sections, we present and discuss the methodology and findings from our study of three middle school science teachers who used the TAP-inclusive unit as a central component of their designed lessons for classroom learning. We also describe and discuss our evaluation of students' performance on the assessment item before and after teacher action.

Research Questions

In this study, we address the following questions:

1. What do the LA reveal about student learning?

2. In what ways does the LA dashboard (i.e. TAP) support actionable insight for teachers?

3. In what ways do teachers' pedagogy (i.e. teaching methods and philosophy) influence their LA-informed actions?

Materials and Methods

Participants

Three middle school science teachers in two different schools and districts as well as their 212, 7th grade students participated in this study. Teachers 1 and 3 had 20+ years of teaching experience, and Teacher 2 had less than one year of teaching experience. Although Teacher 3 had previous experience teaching a WISE unit, the previously co-designed unit used in this study (ref. Study 3) was new to all three teachers. Given the recent adoption of the Next Generation Science Standards (NGSS) by the state in which the study was conducted, the study teachers explicitly expressed their need for support in helping their assess their students' progress in developing integrated, three-dimensional knowledge.

Curriculum

For this study, we embedded the previously designed TAP in (ref. Study 4) in a four-lesson, WISE unit on photosynthesis, cellular respiration, and ecosystems designed to target several performance expectations. Each of the four lessons was co-designed by researchers and teachers, in accordance with the KI framework (ref. Chapter 3). The first two lessons of the unit engaged students in instruction about photosynthesis and cellular respiration and were, therefore, the main focus for this study.

Assessments and Rubric

The TAP was targeted to a unit-embedded assessment item that was developed in accordance with NGSS guidelines (Achieve, 2018) for the NGSS performance expectation, MS-LS1-6, which

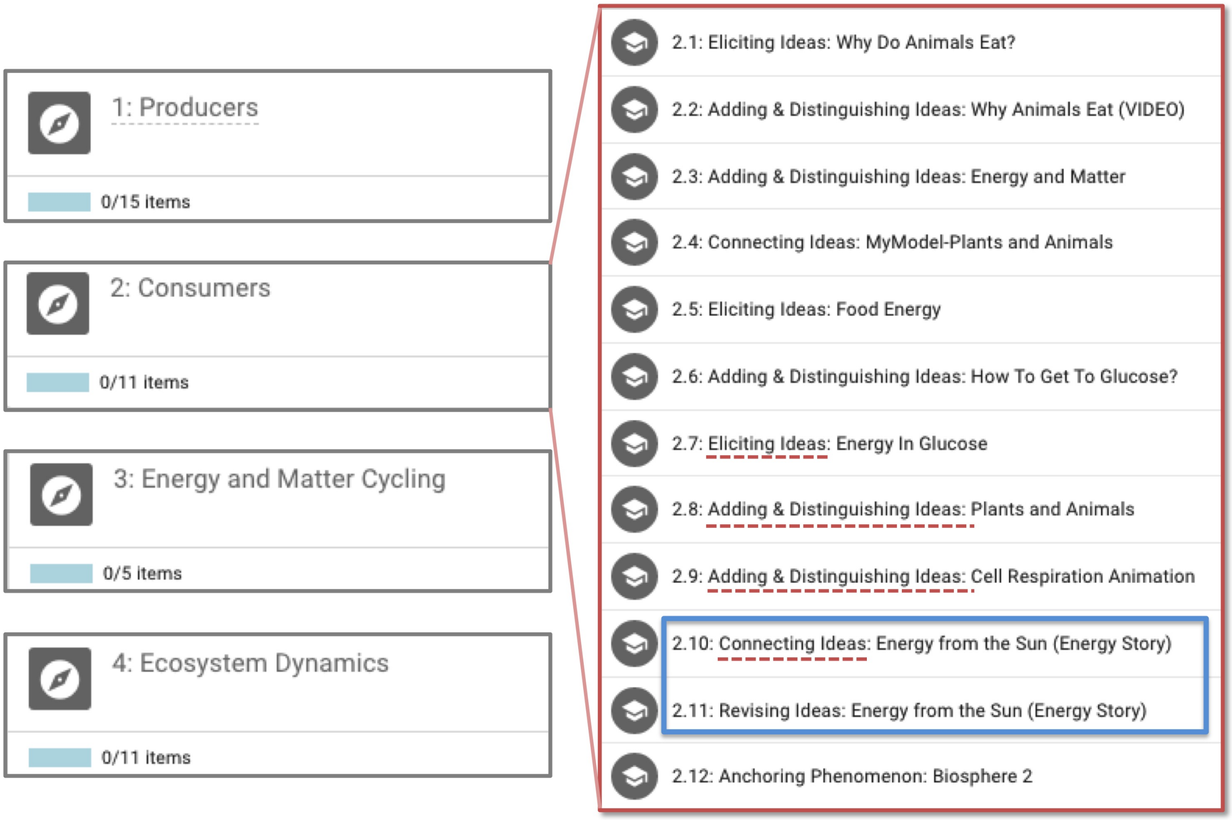


Figure 16: Schematic diagram of the online inquiry science unit. Red dashed lines indicate the steps of the Knowledge Integration process being target by the unit activity. Blue box indicates the steps associated with the Initial Explanation item (2.10) and the Reflection Explanation item (2.11).

calls for students to "Construct a scientific explanation based on evidence for the role of photosynthesis in the cycling of matter and flow of energy into and out of organisms" (National Research Council, 2013). The item engaged students in the *connecting ideas* step of the KI process and addressed the NGSS performance expectation, MS-LS1-6 (Figure 18). MS-LS1-6 In two consecutive steps at the end of lesson 2, once before teachers reviewed the TAP (referred to as Initial Explanation) and once after their learning design modifications (referred to as Reflection Explanation), the assessment item prompted to explain how the sun helps animals to survive. To measure students' performance on the Initial and Reflection versions of this item, we relied upon a previously validated performance expectation (PE) rubric (ref. Chapter 4; Figure 17). The PE rubric consists of three criteria categories, one for each NGSS dimension. The dimension criteria measure students' written responses for evidence of the integration of the specific DCI and CCC ideas expressed in MS-LS1-6. The SEP/KI dimension criteria measured for the overall integration of normative science ideas related to photosynthesis and how the ideas were used to explain the targeted phenomena (i.e. the cycling of matter and flow of energy into and out of organisms).

Coherence Score Description	Score Level	Idea Score Description
Off-task response	1	No discussion of target ideas
No link - Alternative or invalid ideas	2	Partial discussion of target ideas
Partial link - Normative ideas without any scientifically valid links between normative ideas	3	Full discussion of target ideas
Full link - One scientifically valid links between normative ideas	4	
Complex link - Two scientifically valid links between normative ideas	5	
Scientifically Valid Link Description		**Photosynthesis & Producer/Consumer Relationships (DCI)**
Energy transformation: One type of energy can be transformed into another type of energy. Light energy is transformed into chemical energy during photosynthesis.		Idea #1: Full = CO_2 + H_2O --> (via arrangement or chemical reaction) glucose + oxygen, uses energy from sun/light to do photosynthesis reaction Not good enough for partial credit to just say that the plant gets/uses energy from the sun to grow, need to say or describe photosynthesis
Matter transformation: Reactants, such as carbon dioxide and water, are transformed into products, glucose and oxygen.		Idea #2: Full = Explicit statement about what specifically the PLANT uses glucose/food (not CO_2, H_2O, light) for: growth, energy, stored, repair, seed production
Energy–matter relationship: Energy is required to initiate a chemical reaction (bond breaking). Chemical energy is stored in glucose (matter).		
		Energy Transfer Drives Matter Cycling (CCC)
		Idea #1: Full = Energy (any type of relevant energy) and matter (any type of relevant matter) moves WITHIN THE PLANT during photosynthesis
		Idea #2: Full = Energy from the sun gets to animals when they eat photosynthetic plants, directly or indirectly. (i.e. when animals EAT plants or plant-eating animals breathe in oxygen for food/energy)

Figure 17: Rubric used for scoring the assessment items.

To assess students' starting and ending levels of knowledge integration related to photosynthesis and cellular respiration, we used an assessment item in the pretest and post-test for the unit that was similar to the Initial/Reflection Explanation item. Student responses to this pre-/post-test item were also evaluated using the PE rubric.

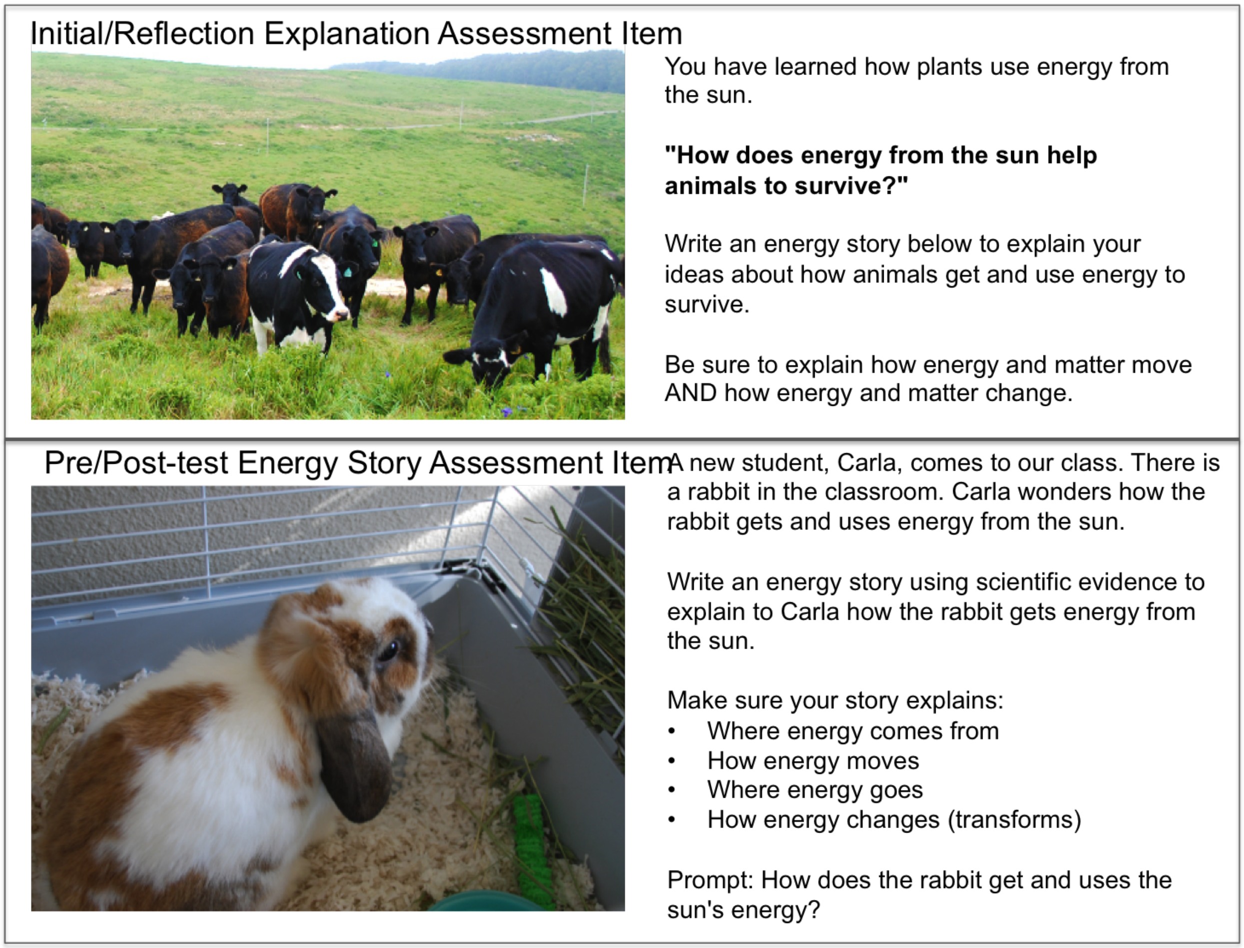


Figure 18: Prompts for the Initial/Reflection Explanation items (top) and the Pre/Post-test assessment items (bottom). Note: The Reflection Explanation item prompt had the statement “Revise your energy story to explain your new ideas about how animals get and use energy to survive.”

TAP Description and Availability

We divided the TAP display into four primary sections: Description, Class Report, Recommended Action, and Student Completion (Figure 19).

Description section. This section identified the step in the unit where the assessment item could be found, as well as a hyperlink to the targeted NGSS performance expectation, MS-LS1-6. This section also included a drop-down menu where teachers could change the data set used for the analysis, specifying a particular class period or choosing an "All periods" option. From this section, teachers could also see the percentage of students whose data was included in the analysis.

Class Report section. This section included a description of the item prompt and learning objectives, as well as a histogram of student scores for each NGSS dimension. Also included in this section was a narrative summary of the analysis and an example of a response that illustrated

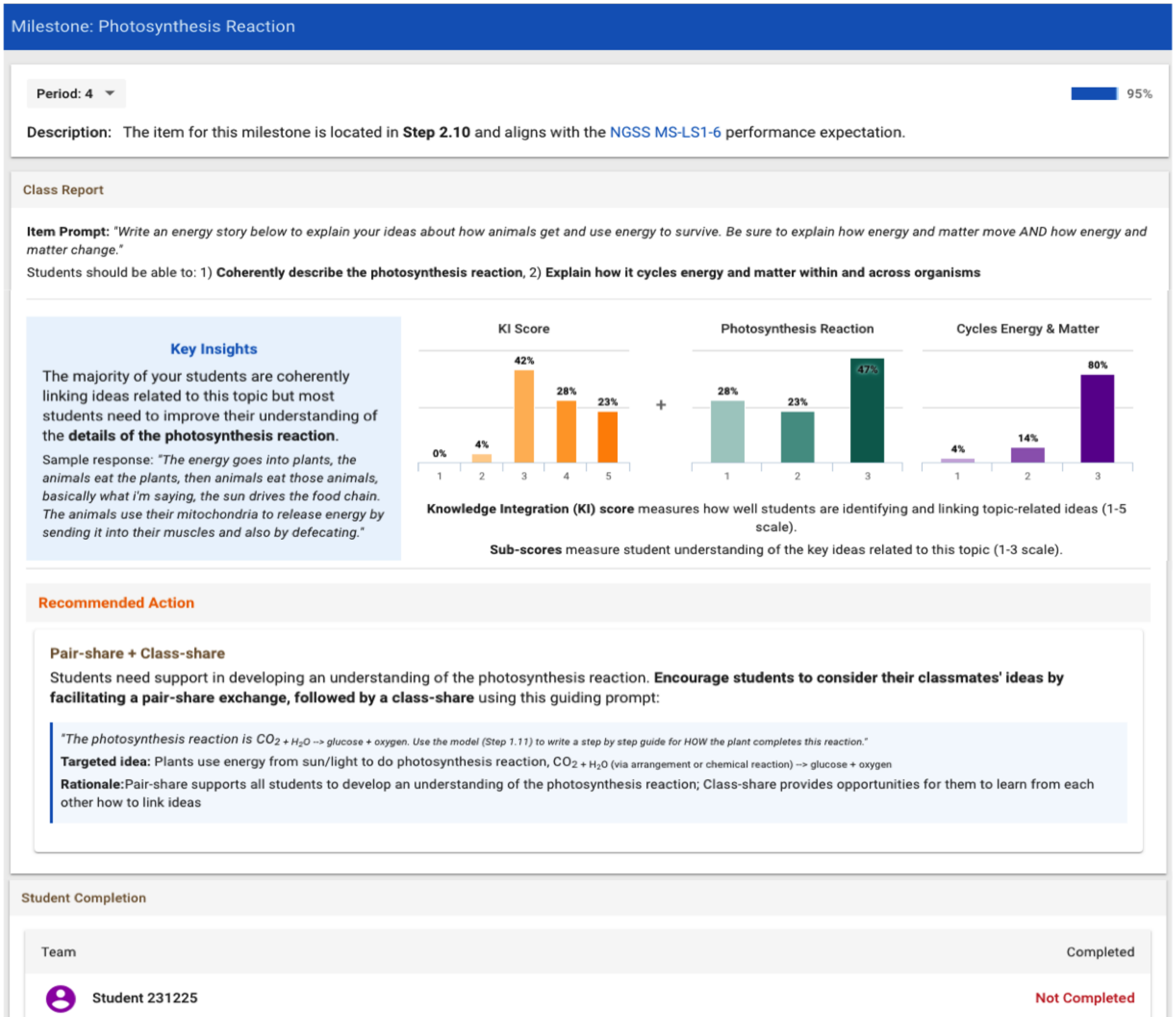


Figure 19: A screenshot of the TAP report targeted to the WISE Photosynthesis Initial and Reflection assessment item.

the displayed profile of scores.

Recommended Action section. This section included a recommended activity structure that teachers could use to address students' learning needs as indicated in the Class Report section. It also included a rationale for why the recommendation was made and brief guidance for how to implement the activity structure. Additionally, this section explicitly stated the ideas being assessed.

Student Completion section. This section included a class roster indicating students' completion status for the targeted assessment item.

TAP availability. The TAP was located in the teacher interface of the WISE platform and accessible to teachers via the Grading Tool feature after 75% of students completed the Initial Explanation item. It presented LA corresponding to class-aggregated data of students' autoscored responses to the assessment items and updated in real-time based on students' performance on the Reflection Explanation.

Data Sources, Collection and Analysis

Using the Grading Tool in the teacher interface of the platform, teachers could see their students' names, responses, and auto-generated scores, however, researchers could only access anonymized versions of this information through the WISE system. From this interface, researchers exported logged student data associated with the assessment items (i.e. Initial/Reflection Explanation and pre-/post-test item). Included in the exported data were automatically generated scores for students' assessment item responses. The scores were automatically generated by a c-rater algorithm that was trained on 1,000+ student responses that were human-scored using the PE rubric. A previous study demonstrated that the computer-human scoring agreement for this item is approximately 70+% for all three rubric dimensions (Riordan et al., 2020).

To determine whether students achieved learning gains after the instructional intervention, we performed McNemar's tests on students' autoscored responses from the Initial to Reflection Explanation item. To determine if students experienced long-term learning gains, we conducted the same analysis on students' autoscores on the pretest and post-test item.

To understand teachers' pedagogy, we conducted semi-structured interviews with each teacher before (pre-TAP) and after viewing the TAP generated from their class data (post-TAP). We also conducted classroom observations to document the pedagogical actions that teachers took after viewing data related to their students' performance on the Initial Explanation item. During the pre-TAP interview, we introduced the assessment items to teachers and solishortshortcited their feedback on the TAP features, using a sample TAP display. Also, during the pre-TAP interview, we solishortshortcited information from teachers regarding their typical assessment strategies and their expectations and interpretations of their students' performance on the embedded assessment item. The post-TAP interview was conducted either after the class period or after the school day. During the post-TAP interview, we asked teachers to describe their pedagogical actions in response to student data and provide a rationale for why they chose to implement them. Teachers were also asked how the TAP influenced their instructional intervention and subsequent instruction. The transcripts of these interviews were analyzed for evidence of the teachers' pedagogy, specifically their beliefs and practices regarding teaching, student learning, and assessments.

Results

RQ 1: Evidence of student learning

To make the LA presented in the TAP interpretable for teachers, the distribution of students' scores along each NGSS dimension were summarized using histograms. However, in this section, we report these results in tabular form and report the results of our extended analysis examining the statistical significance in the distribution changes between timepoints (i.e. Initial/Reflection and Pre-/Post-test). There were differences across teacher regarding completion of the assessment items at the various timepoints. Teachers 1 and 3 completed the assessments at all four timepoints, however, students from Teacher 2 only completed the assessments at the pretest and the Initial and

Reflection timepoints. Of note regarding the timing of the assessments, students of Teachers 1 and 2 completed the unit in five weeks and those of Teacher 3 completed the unit in one week.

Student Learning from Initial to Reflection. The majority of each teacher's students completed both the unit-embedded assessment item at both the initial and reflection timepoints (Teacher 1: 84%, 81/97; Teacher 2: 84%, 79/94; Teacher 3: 100%, 21/21). To simplify the analysis and interpretation of student scores, we collapsed the criteria levels for each dimension to generate binary variables that represented the presence of photosynthesis-related ideas that are either unlinked (scores 1-3) or linked (scores 4 or 5) for the SEP/KI dimension and, for the DCI and CCC dimensions, whether the target ideas were not fully integrated (score of 1 or 2) or fully integrated (scores of 3).

The results of the McNemar's tests revealed that all the students for each teacher had a statistically significant ($p < 0.05$) shifts in scores from Initial to Reflection along the three NGSS learning dimensions (Table 11). The vast majority of students expressed unlinked (SEP/KI) and not fully integrated (DCI and CCC) ideas at the time of the Initial Explanation. However, in all three teachers' classrooms, there were students who shifted from unlinked to linked SEP/KI ideas (Teacher 1: 11%; Teacher 2: 8%; Teacher 3: 33%) and from not fully integrated to fully integrated DCI (Teacher 1: 7%; Teacher 2: 9%; Teacher 3: 38%) and CCC ideas (Teacher 1: 14%; Teacher 2: 15%; Teacher 3: 38%). The shifts along the CCC dimension were the greatest for all three teachers' students.

Initial	Reflection		
DCI $\chi^2(1) = 6.00$ $p_{exact} = 0.0312$*	Not Present	Present	Total
Not Present	64 (79%)	6 (7%)	70 (86%)
Present	0 (0%)	11 (14%)	11 (14%)
Total	64 (69%)	17 (21%)	81 (100%)
CCC $\chi^2(1) = 6.23$ $p_{exact} = 0.0225$*	Not Present	Present	Total
Not Present	45 (56%)	11 (14%)	56 (69%)
Present	2 (2%)	23 (28%)	25 (31%)
Total	47 (58%)	34 (42%)	81 (100%)
SEP/KI $\chi^2(1) = 6.40$ $p_{exact} = 0.0215$*	Unlinked	Linked	Total
Unlinked	58 (72%)	9 (11%)	67 (83%)
Linked	1 (1%)	13 (16%)	14 (17%)
Total	59 (73%)	22 (27%)	81 (100%)

Teacher 1 - Initial vs. Reflection

*p<0.05

Initial	Reflection		
DCI $\chi^2(1) = 7.00$ $p_{exact} = 0.0156^*$	Not Present	Present	Total
Not Present	70 (89%)	7 (9%)	77 (97%)
Present	0 (0%)	2 (3%)	2 (3%)
Total	70 (89%)	9 (11%)	79 (100%)
CCC $\chi^2(1) = 9.31$ $p_{exact} = 0.0034^{**}$	Not Present	Present	Total
Not Present	55 (70%)	12 (15%)	67 (85%)
Present	1 (1%)	11 (14%)	12 (15%)
Total	56 (71%)	23 (29%)	79 (100%)
SEP/KI $\chi^2(1) = 6.00$ $p_{exact} = 0.0312^*$	Unlinked	Linked	Total
Unlinked	69 (87%)	6 (8%)	75 (95%)
Linked	0 (0%)	4 (5%)	4 (5%)
Total	69 (87%)	10 (13%)	79 (100%)

Teacher 2 - Initial vs. Reflection

*p<0.05; **p<0.01

Initial	Reflection		
DCI $\chi^2(1) = 8.00$ $p_{exact} = 0.0078$**	Not Present	Present	Total
Not Present	11 (52%)	8 (38%)	19 (90%)
Present	0 (0%)	2 (10%)	2 (10%)
Total	11 (52%)	10 (48%)	21 (100%)
CCC $\chi^2(1) = 8.00$ $p_{exact} = 0.0078$**	Not Present	Present	Total
Not Present	4 (19%)	8 (38%)	12 (57%)
Present	0 (0%)	9 (43%)	9 (43%)
Total	4 (19%)	17 (81%)	21 (100%)
SEP/KI $\chi^2(1) = 7.00$ $p_{exact} = 0.0156$*	Unlinked	Linked	Total
Unlinked	10 (48%)	7 (33%)	17 (81%)
Linked	0 (0%)	4 (19%)	4 (19%)
Total	10 (48%)	11 (52%)	21 (100%)

Teacher 3 - Initial vs. Reflection

*p<0.05; **p<0.01

Table 11: Frequency of students by teacher and score dimension with either unchanged or improved performance on the Reflection Explanation item compared to their Initial Explanation item performance. McNemar's Chi-squared and exact significance probability are included. Colors are gradated to reflect frequency amounts, with darker gradations reflecting higher frequency.

Student Learning from Pretest to Post-test. We simplified the analysis and interpretation of student' pre-/post-test scores by collapsing the three original criteria levels for each dimension into binary variables that represented the presence of photosynthesis-related ideas that are either non-normative (scores of 1 or 2) or normative (scores 3-5) for the SEP/KI dimension and whether the target DCI and CCC ideas were either not present (score of 1) or present (scores of 2 or 3). Subsequently, we conducted McNemar's tests on their scores from the pretest and post-test item for each dimension to evaluate whether students retained the Initial to Reflection Explanation learning gains till the completion of the unit. Since, Teacher 2's students did not complete the post-test, their scores were excluded from this analysis.

Of the students who completed both the pretest and post-test, 55 (56%) in Teacher 1's class and 18 (82%) in Teacher 1's class, only Teacher 1's students had statistically significant ($p<0.05$) shifts in scores along the three dimensions from pretest to post-test (Table 12).

For the SEP/KI dimension of the pre-/post-test assessment item, 25% of Teacher 1's students shifted from non-normative to normative photosynthesis related ideas, 19% shifted from not expressing any target DCI ideas to expressing the target ideas, and 25% made a similar shift along the CCC dimension. Although the shifts observed in Teacher 3's students' pre-/post-test scores were not statistically significantly, it's notable that they began the unit instruction expressing more normative and target ideas for all three dimensions than did Teacher 1's students. Specifically, for Teacher 3, at the time of pretest, 72% expressed normative ideas related to photosynthesis, 44% of students expressed target DCI ideas, 67% expressed target CCC ideas.

Pretest	**Post-test**		
DCI $\chi^2(1) = 7.36$ $p_{exact} = 0.0117^*$	Not Present	Present	Total
Not Present	42 (79%)	10 (19%)	52 (98%)
Present	1 (2%)	0 (0%)	1 (2%)
Total	43 (81%)	10 (19%)	53 (100%)
CCC $\chi^2(1) = 6.25$ $p_{exact} = 0.0213^*$	Not Present	Present	Total
Not Present	29 (53%)	13 (25%)	41 (77%)
Present	3 (6%)	9 (17%)	12 (23%)
Total	31 (58%)	22 (42%)	53 (100%)
SEP/KI $\chi^2(1) = 10.29$ $p_{exact} = 0.0018^{**}$	Non-normative	Normative	Total
Non-normative	33 (62%)	13 (25%)	46 (87%)
Normative	1 (2%)	6 (11%)	7 (13%)
Total	34 (64%)	19 (36%)	53 (100%)

Teacher 1 - Pretest vs. Post-test Performance

*$p<0.05$; **$p<0.01$

Pretest	Post-test		
DCI $\chi^2(1) = 1.00$ $p_{exact} = 0.6250$	Not Present	Present	Total
Not Present	6 (33%)	3 (17%)	9 (50%)
Present	1 (6%)	8 (44%)	**9 (50%)**
Total	7 (39%)	**11 (61%)**	18 (100%)
CCC $\chi^2(1) = 1.00$ $p_{exact} = 0.6250$	Not Present	Present	Total
Not Present	2 (11%)	3 (17%)	5 (28%)
Present	1 (6%)	12 (67%)	**13 (72%)**
Total	3 (17%)	**15 (83%)**	18 (100%)
SEP/KI $\chi^2(1) = 1.00$ $p_{exact} > 0.9999$	Non-normative	Normative	Total
Non-normative	4 (22%)	1 (6%)	5 (28%)
Normative	0 (0%)	13 (72%)	**13 (72%)**
Total	4 (22%)	**14 (78%)**	18 (100%)

Teacher 3 - Pretest vs. Post-test Performance

Table 12: Frequency of students by teacher and score dimension with either unchanged or improved performance on the post-test Energy Story item compared to their pretest performance. McNemar's Chi-squared and exact significance probability are included.

RQ 2: TAP-mediated actionable insight

To explore how the TAP mediated teachers' insight regarding student learning and their subsequent pedagogical action, we analyzed the transcripts and notes from semi-structured interviews with teachers in combination with the classroom observation notes.

TAP features that support an understanding of student learning. During the pre-TAP interviews, we solicited teachers' feedback on the TAP features. As teachers reviewed the TAP, they scrolled through and audibly read to themselves each section of the TAP. All three teachers reported that they expected the TAP to support them in understanding student learning. They identified the TAP's alignment with an assessment targeted to a specific NGSS performance expectation as a key affordance (*Description* section). This TAP feature was designed to enable the teachers to know what to attend to amongst all the learning activities in the online unit. For example, Teacher 1 commented that having LA associated with a particular assessment item allowed her to redirect her time and energy toward extensively examining student performance on that item rather than giving cursory attention to all items. For Teachers 2 and 3, the TAP alignment with the NGSS photosynthesis performance expectation helped them feasibly determine whether their students were "getting it or not". Teacher 2 also identified the "Targeted Ideas" (*Recommended Action* section) as a valuable instructional tool as they would help him to specifically evaluate what information his students did and did not understand. Teacher 3 viewed the TAP as providing wholistically valuable feedback consisting of "a real analysis of the data" (a reference to the score histograms in the *Class Report* section) that allowed him to support his students to engage in an important aspect of critical learning, namely revising their ideas. All teachers stated that the graphical presentation of the information facilitated their quick understanding of students' performance (*Class Report* section). Teachers slowed their reading as they read the Key Insights and Recommended Action section. All teachers stated that they valued the recommended actions as they gave them specific ideas for how to address their students' learning needs, especially Teacher 2, given his limited teaching experience. They also expressed a desire to have the scoring rubric and students' responses directly accessible via the TAP as opposed to having to go to a different section of the Grading Tool (a reference to the *Student Completion* section).

Teacher expectations for student learning. To further assess whether and how the TAP supported teachers to understand their students' learning, teachers were also asked during the pre-TAP interview what expectations they had for students' learning, specifically in terms of their performance on the Initial Explanation item. All three teachers said that by the time students reached Initial Explanation item they expected them to know the basics of photosynthesis since it was positioned at the end of instruction on photosynthesis and cellular respiration.

Teacher 1 and 2's expectations were based on the three weeks of instruction they provided their students prior to engaging the online unit. Despite the fact that Teacher 1 and 2 followed a similar lesson plan, what constituted the basics differed by teacher. For Teacher 1, the basics meant knowing that plants take in carbon dioxide and water, and that they make glucose and oxygen. However, for Teacher 2 the basics meant knowing that animals get energy from plants, and plants get energy from the sun. He commented that he would expect students to struggle with the chemical reaction aspect of photosynthesis, recalling that his students had difficulty remembering the term "glucose". Contrastingly, Teacher 3 provided his students with one class period of instruction prior to the online photosynthesis unit. Although Teacher 3 did not articulate exactly what knowledge represented the basics. His expectation was that students would know the photosynthesis basics from prior instruction starting in elementary school.

Interpretation of TAP analytics. During the post-TAP interview, we asked teachers to share their interpretation of the LA presented. Before sharing their interpretation, all three teachers asked for more information about the algorithm used to autoscore students' responses. Teacher 1 wanted to know whether the algorithm could understand what students meant if their response included chemical formulas and whether the algorithm could tell if students copied and pasted portions of their response from the internet. Teachers 1 and 2 wanted to know whether the algorithm could decipher misspelled words. They were told that the algorithm was trained on over 1000 student responses, many of which used chemical formulas. They were also told that while spelling errors were not problematic for score assignment, the algorithm could not determine if the responses were copied and pasted from the internet. The teachers also asked which aspects of students' responses distinguish one score level from another. For Teachers 1 and 2, these questions were generated after they read through their students' responses in the Grading Tool section of the teacher interface. They commented on what they perceived as discrepancies between the score they would have given some of their students' response and the autogenerated score. For example, Teacher 1 noted that the algorithm assigned student responses that simply discussed the basics with a score of 3, whereas she would have assigned them a score of 1.

Once the teachers understood the way the algorithm applied the rubric to assign scores, they identified score levels of 4 and 5 as the most desirable in terms of student performance. With this lens, they interpreted the graphical data as binary, either above a 3 or not. This provided them with a general sense of whether or not students adequately learned the topic. Teachers 1 and 2 expressed a need to read through student responses in the Grading Tool to gain a richer understanding of student thinking. For Teacher 3, on the other hand, the graphical data in the TAP provided him with a sufficient level of understanding regarding his students' learning to immediately implement the recommended instructional intervention.

Teachers' Pedagogical Actions

For two out of three periods for Teacher 1 and Teacher 3's period, the TAP indicated that the majority of students understood the CCC ideas but needed support to understand the DCI ideas (Figure 20, Recommended Action 1). For Teacher 1's remaining period and all three of Teacher 2's periods, the TAP indicated that students needed support to both understand and link the CCC ideas and the DCI ideas (Figure 15, Recommended Action #2).

During the classroom observations, we observed that all teachers took pedagogical actions in the form of instructional interventions in response to the TAP, albeit with varying degrees of alignment to the KI process, which the unit's learning design supported (Figure 16). Teacher 1 and 2 created their own interventions, while Teacher 3 relied upon the recommended action in the TAP. Teacher 2 and 3's interventions incorporated activities in the WISE unit, whereas Teacher 1's intervention drew upon her own activities.

Teacher 1's pedagogical action. In response to her students' performance on the Initial Explanation item, Teacher 1 decided to engage her students in a revised version of a previous class activity. In this activity, students were given strips of paper with key words or images related to photosynthesis and cellular respiration, the latter of which was not included in the first implementation of this activity prior to engaging the unit instruction (Figure 21, top left image). Students worked in groups (3-4 students) to organize the words and images into a coherent narrative. Students could use as many of the words or images and create additional words/images on the provided blank strips. Once the groups constructed a narrative, they vocalized it to the teacher who provided feedback regarding its thoroughness in relation to the target ideas. Upon presenting a "satisfactory" narrative or when the class period was ending, whichever was first, the groups completed the Reflection Explanation item.

Teacher 1 said the primary goal of the activity was to support her students in constructing a coherent narrative of how photosynthesis and cellular respiration are connected and how that

Recommended Action

Pair-share + Class-share

Students need support in understanding and linking the details of the photosynthesis reaction. **Encourage students to consider their classmates' ideas by facilitating a pair-share exchange, followed by a class-share** using this guiding prompt:

> *"Use evidence from the model (Step 1.11) to describe exactly how energy from the sun ends up in the glucose that plants make during photosynthesis"*
>
> **Targeted idea:** Plants use energy from sun/light to do photosynthesis reaction, CO_2sub> + H_{20} (via arrangement or chemical reaction) --> glucose + oxygen
>
> **Rationale:**Pair-share supports all students to use their understanding of the how photosynthesis cycles energy and matter to develop an understanding of the details of the photosynthesis reaction; Class-share provides opportunities for them to learn from each other how to link ideas

Knowledge Integration Process	Recommended Action #1 (above)	Recommended Action #2 (below)
Elicit Ideas	Sharing with partner	Looking for evidence in the model
Add Ideas	Exploring model	Reading peers responses
Distinguish Ideas	Using evidence to describe how glucose gets energy from the sun	Determining whether to support, refute, or clarify their peers ideas
Connect Ideas	Class discussion facilitates synthesis of ideas	Using evidence to support, refute, or clarify their peers ideas

Recommended Action

Jigsaw based on KI score

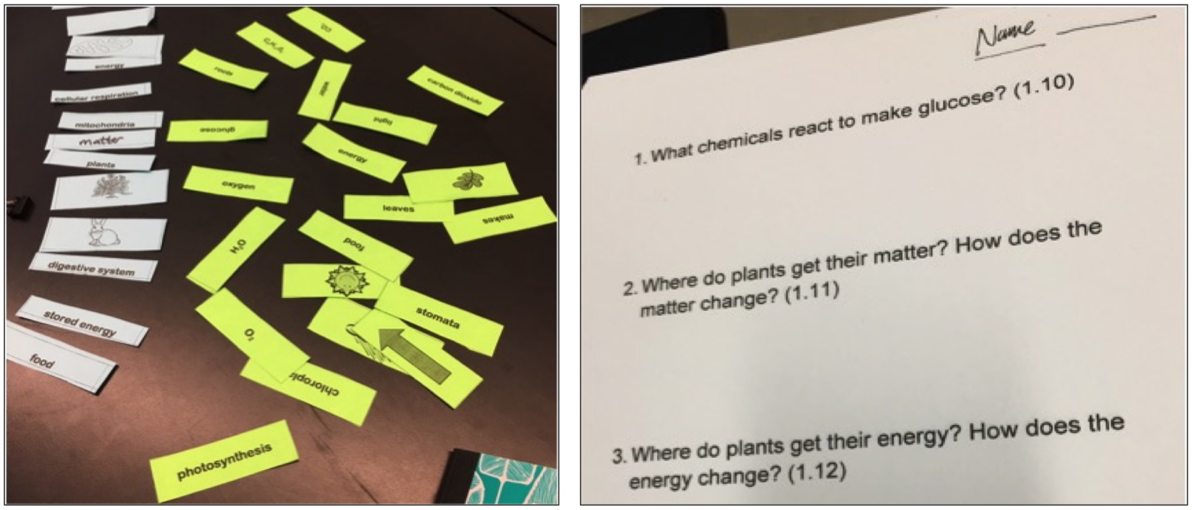
Students need support in both developing and linking their ideas about this topic. **Have students engage in a jigsaw discussion activity, pairing up teams that have different KI scores.** Use this guiding prompt:

> *"Find evidence in the model (Step 1.11) to either support, refute, or clarify the claims made in this response (use responses from each KI level)."*
>
> **Targeted ideas:** 1) Plants use energy from sun/light to do photosynthesis reaction, CO_2sub> + H_{20} (via arrangement or chemical reaction) --> glucose + oxygen, 2) Energy from the sun gets to animals when they eat photosynthetic plants
>
> **Rationale:** Jigsawing based on KI score allows students to develop the particular skill they need (1/2: gather ideas to support claim, 3: gather evidence to refute claim, 4/5: identify ways to clarify claims). The mixed groups encourages all students to learn from each other either new ideas, how to coherently link ideas, or how to clarify/elaborate ideas.

Figure 20: The Recommended Actions that teachers received in the TAP (top, bottom) and how each action aligned with the steps of the Knowledge Integration process.

connection leads to the flow of energy and cycling of matter. She stated that this focus came after reading through her students' responses and noticing that while many of them discussed photosynthesis few discussed cellular respiration. As Teacher 1 implemented her intervention, she explained that the next time she ran the unit she would have the settings adjusted to allow her students to see their scores on the Initial and Reflection Explanation item. She reasoned that her students might be motivated by their initial poor performance to learn more and revise, and subsequently be encouraged by their score improvement.

Teacher 2's pedagogical action. After viewing the TAP report, Teacher 2 read all of his students' responses and constructed a worksheet of short-answer questions related to the assessment prompt (Figure 21, top right image). Each question on the worksheet indicated where in the photosynthesis unit students could find the answer. Teacher 2 responded to students' clarifying questions by rephrasing the worksheet questions. Before the period ended, students were instructed to complete the Reflection Explanation item.



Knowledge Integration Process	Teacher 1 Storyboard Activity	Teacher 2 Worksheet Activity	Teacher 3 Peer-to-Peer Sharing
Elicit Ideas	Connecting the terms to known ideas	————	Sharing responses
Add Ideas	Exploring ideas related to unknown terms	Looking for correct answer on specified unit step	Listening to responses
Distinguish Ideas	Determining which ideas to include in the story	————	————
Connect Ideas	Connecting the ideas to make a coherent and accurate story	Revising response to include ideas from worksheet	Revising response to include peers' ideas until satisfied with score

Figure 21: The alignment of teachers' learning design modifications with the steps of the Knowledge Integration process. Top left image: Teacher 1's storyboard activity materials. Top right image: A portion of Teacher 2's worksheet activity.

Regarding his students' ability to engage this activity, Teacher 3 stated that, in his estimation, few of his students had developed the skill "to go back and reference material," and as a consequence were not going to benefit from his worksheet activity.

Teacher 3's pedagogical action. After viewing the TAP report, Teacher 3 read the TAP report to his class. He described the number of students at each score level and the scale for each score. He read the Key Insights and Recommended Action sections to the class. He then instructed them to complete the Reflection Explanation item. Per Teacher 3's request, we adjusted the settings of the online platform so that the students could see their autogenerated KI score as they completed the Reflection Explanation item. Regarding his rationale for making the score visible to his students Teacher 3 expressed his belief that students are motivated by games and that seeing their score would have the effect of gamifying the revision process. He also expressed a belief that such motivation would encourage them "to cognitively understand what's going on" in terms of the science content. Once students started submitting their revised responses, Teacher 3 used the live update of the TAP graphs to monitor the changes in students' scores and shared these updates with them until the class period ended. Students engaged in revision and resubmission until they were satisfied with their score or the class period was over, whichever came first. During this revision process, students queried each other regarding their scores and referenced each other's responses during small group conversations about how to improve their score. Teacher 3 was aware of this behavior and identified it as valuable for learning, stating that it functioned to provide students with an "end goal", an exemplar of how to construct their responses. Teacher 3 expressed a desire for additional TAP modifications that were unavailable at the time. For example, he wished that he could press a button to send the Recommended Action section of the TAP or a customized action (e.g. revisiting specific activities in the unit, providing sample responses to critique and revise) to the class.

RQ 3: The TAP's Influence on Teacher Pedagogy

Perspectives on learning and assessment. We further analyzed the post-TAP interview transcripts for evidence of belief statements that reflect their teaching pedagogy, specifically, their perspective on teaching, student learning, and assessment. With this analysis, we sought to situate teachers' pedagogical in an understanding of their teaching pedagogy to determine whether and how the TAP influenced it. The three teachers had different perspectives on teaching, student learning, and assessment.

Teacher 1's pedagogy. Teacher 1 noted that her perspectives on student learning were developed from over 20 years of teaching experience. She believed that students "need more than just seeing stuff on a screen, they need to move stuff around and sort of make sense making out of it". For student learning in a TEL environment she commented, "When they're doing things on the computer, even if it says to talk to a partner, it's still very individualized and very much working in your own space and in your own mind, and so you need to share ideas with others to truly understand them. And so I have to create situations where that's happening." To implement this perspective, she developed a large repertoire of what she termed "kinesthetic-verbal" activities. The kinesthetic-verbal activities require students to physically manipulate objects while simultaneously engaging in small group discourse to explain science ideas. She noted that these types of activities create space for students to productively struggle with, develop, and articulate their understanding of the content in ways that suit them. She identified these kinesthetic-verbal activities as necessary precursors for students being able to articulate their ideas in writing and summarized the process as "work-talk-revise". Teacher 1 expressed a belief that there is no single right way of explaining science ideas and valued these kinesthetic activities for their ability to surface multiple, and equally correct explanations. She stated that when high-performing students communicate their ideas during kinesthetic-verbal activities, their ideas get solidified and simultaneously function to help low performing students gain a better understanding. She further stated that through the discourse she is able to evaluate each student regarding whether and to what extent students are appropriately using science vocabulary, which she viewed as a key determinant of science understanding.

Teacher 2's pedagogy. Similar to Teacher 1, Teacher 2 identified verbal explanations as a valuable means to gauge student learning. However, in contrast to Teacher 1, Teacher 2, who only had 3 months of teaching experience, viewed one-on-one, teacher-student conversations as the most effective assessment strategy rather than small group, student-student exchanges. He stated that his perspective on the value of this strategy was based on his recognition of students' difficulty in articulating their thoughts in writing. He stated, "...if I sit with them or come over to them one-on-one and kind of talk it through with them, they usually reveal more of what they know." He viewed students' written responses as representing the ideas they were "confident enough to put down." Teacher 1 also expressed the perspective that students' understanding of science ideas and their confidence in writing those ideas would increase as they had more exposure to those ideas. He used the typical strategy of having his students "go back and re-think" about information they did not seem to understand. He expressed a belief that students truly understood a science idea if they can reproduce the correct answer several days later. This belief is reflected in his comment regarding assessment, he stated that he would "give them another day before going back and letting them revise, like let it soak in a little longer to see if it really sticks." He made a distinction between remembering and learning, where the former was synonymous with short-term recall and the latter with long-term recall.

Teacher 3's pedagogy. Like Teacher 1, Teacher 3 developed his perspective on learning and assessment over his 20+ years of teaching experience. He viewed learning as dictated by two primary factors, interest and intrinsic intellectual capacity, the former being the only factor that he, as the teacher, would be able to influence. Teacher 3 expressed a belief that his actions as a teacher were more effective when they focused on inspiring and encouraging students rather than providing them with remedial support. He commented, "My job is to hook 'em. Hook 'em for life, right? Science for life." For the students that he recognized as having the intellectual capacity to learn, he saw his job as providing them with the skills to learn on their own. Consistent with this perspective, he expressed a view that assessments are a means of giving students credit for engaging the learning process, whether it be participation in the "hook 'em" activities or making use of their intellectual ability to critically think about and express science ideas. Similar to Teachers 1 and 2, Teacher 3 expressed a belief that learning took place through conversation and that regardless of whether students get assistance to complete formal assessments, like homework assignments and tests, "that, during that process, at least conversations are happening." Summarizing his perspective on assessment, Teacher 3 stated, "I'm not going to spend all my energy on assessment when I want to just give them opportunity to explore and learn a lot."

Discussion

In this study, we evaluated a teacher LA dashboard embedded into a previously co-designed WISE Photosynthesis unit (ref. Study 3). To facilitate interpretability and actionability, we developed our LA dashboard, the TAP, using the educational data storytelling approach (Echeverria, Martinez-Maldonaldo, et al., 2018). To promote pedagogical actions that improved student learning, we aligned the LA in the TAP with the KI framework, a constructivism-grounded pedagogical framework shown to support science inquiry learning (Vitale et al., 2016; Visintainer & Linn, 2015). Since the KI framework characterizes learning as the integration of prior and new ideas relevant to the explored topic, we designed the TAP to present teachers with LA about how well their students' integrated their ideas about the role of photosynthesis in the cycling of matter and the flow of energy across all three NGSS dimensions (i.e. SEP, DCI, and CCC; Figure 19). To support teachers' actionable insight, the TAP provided teachers with a graphical and narrative summary of auto-generated scores for students' responses to the embedded assessment along each dimension of the NGSS. We included a KI-aligned recommendation, based on the profile of students' scores, for how to take targeted pedagogical action.

We conjectured that the alignment of the TAP with the NGSS-aligned and KI-based assessment item would allow teachers to provide students with targeted support towards integrating their developing ideas. Our results demonstrate the ability of theory-grounded LA to provide teachers with pedagogically valuable information to support student learning (Mangaroska & Giannakos, 2018; Gašević et al., 2017; Reimann, 2016).

TAP features supported actionable insight

While the TAP did not provide direct access to student responses, Teacher 1 and 2 nevertheless navigated to the responses and used them to develop a nuanced understanding of their students' understanding. These teachers expressed that the TAP graphs and Key Insights motivated their inquiry into student thinking. Display of TAP analytics and their students' responses also led to teachers' inquiry into the scoring algorithm and rubric. Thus, understanding the logic used to generate the analytics seemed necessary for teachers to develop a TAP-informed understanding of student learning. This finding underscores the need for greater transparency in the technical aspects of LA development.

Teachers' pedagogy guides their LA-informed actions

Although all three teachers took different pedagogical actions, when asked about the motivation for their specific instructional interventions, all three teachers shortshortcited student performance on the TAP-aligned assessments.

Teacher 1. Recognizing her students need to integrate their ideas about cellular respiration with their photosynthesis ideas, Teacher 1 engaged her students in a revised version of a storyboard activity they previously completed. The storyboard activity is an example of what she termed a kinesthetic-verbal activity, and her decision to use this activity reflects her perspective that learning is best achieved when students do and talk while constructing their understanding. She also used this activity as a formative assessment to determine whether students were able to coherently connect their ideas, which was the learning goal. Teacher 1 restructured her students into table groups to develop their stories, which varied from group to group. This variation was permitted by Teacher 1 and reflected her perspective that in science there are multiple ways of expressing the same ideas.

Teacher 2. Teacher 2's intervention required students to get a single right answer to complete the questions on the worksheet that he created for his intervention. The TAP recommended that Teacher 2's class do a jigsaw activity. In this activity students were to be organized in small groups based on the score level of their response and evaluate a response scored at a different score level. The aim of this activity was to provide students at lower score levels with exposure to and opportunities to discuss new ideas and create opportunities for students at a higher score level to collaborate towards connecting ideas. Although Teacher 2 carefully read the recommended intervention and expressed value in being provided with a targeted recommendation, he did not implement it. We hypothesize that Teacher 2 did not use the recommended intervention because it was not aligned with his perspectives on learning. His intervention worksheet called for students to revisit specific steps in the online photosynthesis unit, which aligned with his perspective that learning results from repeated exposure to the target information. During the intervention he engaged students one-on-one to support them in answering the questions to the best of their ability.

Teacher 3. Teacher 3 utilized the TAP recommendation in his learning design modification, albeit not in the way it was designed. Rather than facilitate a whole class discussion after having his students work in pairs to describe how energy from the sun ends up in glucose based on a model in a previous step, Teacher 3 read to his students, verbatim, the Recommended Action section of the TAP. Although this implementation of the recommended action was not completely consistent with the unit's design intention, it was consistent with Teacher 3's perspective on learning. Teacher 3 believed that once students have the skill to learn it is incumbent upon them to facilitate that process themselves. Moreover, his approach to implementing the recommended action was consistent with his relaxed approach to assessment.

Teachers' instructional interventions impact student learning

While the TAP motivated each teacher to make distinct instructional interventions, these instructional intervention corresponded well with their own perspectives on learning and assessment. Despite the differences amongst their interventions, students of all three teachers had statistically significant shifts in the scores from the initial to reflection time point across all three learning dimensions. This result suggests that in terms of short-term learning, perhaps the most salient factor for improvement is targeted intervention, namely interventions that address students' specific learning needs. For Teacher 1 and 3, that entailed supporting their students to connect ideas about photosynthesis and cellular respiration in terms of animal survival. The impact of this focus is evident in the statistical test results showing that Teacher 1's and 3's students had larger shifts across all three dimensions compared to Teacher 2's students. Teacher 2's targeted intervention entailed directing his students to gain information about the details of the photosynthesis reaction and how it supports plants and animals. The impact of this focus is evidenced by the greatest shift in Teacher 2's students' scores occurring along the DCI dimension, which assessed students' understanding of the photosynthesis reaction.

Of all the teachers, Teacher 3's students had the greatest shift in their scores after the learning design modification. Being able to see their score during while completing the Reflection Explanation seemed to be a highly motivating factor for students. Many continuously revised and resubmitted their response in hopes of getting a higher score, which aligns with Teacher 1's hypothesis regarding the relationship between students seeing their scores and the motivation to develop deeper understanding. Achieving higher scores seemed to be the primary goal for both Teacher 3 and his students.

The finding that only Teacher 1's students had statistically significant shifts in their pre- to post-test scores stands in contrast to the results from the Initial and Reflection Explanation where all teachers' students had statistically significant shifts, with Teacher 3's students having the greatest shifts across all three dimensions. Analysis of Teacher 1's and 3's students' scores after the instructional intervention shows the Teacher 3's students achieved the greatest shifts in scores toward the high end of each dimension, with 38% of his students shifting to an expression of fully integrated DCI ideas, 38% shift to fully integrated CCC ideas and 52% shifting to normative and linked ideas (i.e. SEP/KI score 4 and 5). In contrast, after Teacher 1's intervention, only 7% of her students shifted to expressing fully integrated DCI ideas, 14% shifted to fully integrated CCC ideas, and 9% shifting to normative and linked ideas (i.e. SEP/KI score 4). While none of Teacher 1's students retained their full understanding of DCI and CCC ideas through to the post-test, they did retain some of these ideas, 11% DCI retention and 18% CCC retention, although not statistically significant.

One possible explanation for the difference between the post-test performance of Teacher 1's and Teacher 3's students can be drawn from a comparison between the alignment of these teachers' learning design modifications with the KI framework. Since the KI framework represents a pedagogical strategy for supporting students to construct science knowledge, we expect that the learning design modifications that aligned with the KI framework would yield better results regarding students' long-term science learning. Comparing the KI-alignment of these teachers' learning design modifications shows that Teacher 1's learning design modification was fully aligned with the KI framework while Teacher 3's learning design modification was only partially aligned. Prior research (Wiley et al., 2019) demonstrates the critical role that distinguishing and connect ideas has on long-term learning gains. This leads to the explanation that the students of Teacher 1, as compared to those of Teacher 3 (who had more prior knowledge and greater short-term learning gains), were able to achieve long-term learning gains because her learning design modifications were aligned with the theory-grounded pedagogical framework that guided the development of the TAP analytics.

An alternative explanation is that Teacher 1's students achieved long-term learning gains because they spent more time on the subject. While this explanation is possible, we also found that 55% of Teacher 3's students, who completed the post-test less than 2 days after the intervention, had substantial declines in performance. This finding is even more pronounced when compared to the retention expectations for a random list of numbers that Ebbinghaus and others predicted to be 25-30% (Murre & Dros, 2015).

Our finding that Teacher 3's students had large short-term learning gains but failed to retain those gains in the long-term suggests the need to include retention over time as an important LA outcome measure. If LA are to fulfill the goal of optimizing learning and the learning context, then determining whether LA leads to long-term retention is crucial. The statistical analysis revealed that a large proportion of students in all three teachers' classes did not have shifts in their scores despite the modifications to the learning design. This finding suggests that while the TAP features, including the Recommended Action, support teachers toward actions that improve student learning, they can be improved to make that path clearer and more effective. Taken together, these results highlight the value of aligning an LA dashboard with a learning design developed according to a theory-based pedagogical framework, as doing so supports teachers to take LA-informed actions that promote integrated science knowledge.

Study 5 Conclusions

Results from the evaluation of our LA dashboard, the TAP, aligned with research showing the value of LA dashboards that are interpretable, actionable, and aligned to a theory-grounded learning design. Our results show that designing the TAP in this way helped teachers understand how students were integrating their ideas about the role of photosynthesis in the cycling of matter and flow of energy into and out of organisms. This information helped teachers develop instructional interventions that both aligned with their pedagogy and supported their students in meeting the NGSS learning goal. The observation that teachers' instructional interventions were heavily aligned with their own pedagogy warrants further investigation using interview analysis methods that are more robust than those used in this study (e.g. developing a validated coding scheme). Nevertheless, these preliminary findings are notable and align with other research showing the interplay between teachers' pedagogy and their response to LA (Friend Wise & Jung, 2019).

We also found that teachers' understanding of student learning as represented by the TAP analytics depended on their understanding of the algorithm and logic used to develop student scores. This finding underscores the need for greater transparency in the technical aspects of LA development.

Additionally, we gathered empirical evidence of student learning as a result of LA-informed learning design modifications, thus adding to an area of needed research (Mangaroska & Giannakos, 2018). However, "the true test for learning analytics is demonstrating a longer term impact on student learning and teaching practice" (Gašević et al., 2015, p. 6)). Our finding that students experience long-term learning gains when their teacher implemented instructional interventions that aligned with the underlying pedagogical framework suggests that supporting such actions could strengthen LA dashboards.

Furthermore, by evaluating our LA dashboard with both novice and experienced teachers who taught student populations with advanced and limited prior content knowledge, we gained valuable insight for how to redesign the dashboard to support teacher and student populations with diverse backgrounds. For example, incorporating instructional scaffolds to support students in developing a mechanistic understanding of energy and matter transformation during photosynthesis was an effective strategy for helping students with both advanced and limited prior knowledge developed integrated, three-dimensional knowledge related to MS-LS1-6 (ref. Study 2). The next iteration of our dashboard design could draw on these instructional scaffolds to develop new recommended activities. To further support teachers, the recommended activities could be redesigned to provide explicit alignment with the KI framework. In this way, teachers at all experience levels will understand how to effectively implement the recommended activities in ways that promotes the development of integrated knowledge.

Additionally, the recommended activities could be redesigned to suggest activities based on data associated with subgroups or individual students rather than to aggregated class data. In this way, teachers can tailor their pedagogical actions to support the learning needs of particular students or groups of students. Such redesigns could help teachers attend to students' developing ideas, both collectively and individually.

Chapter 5 Summary

The results from the study in this chapter suggest that when presented in an LA dashboard designed for both interpretability and actionability, LA based on learning-congruent data can support the understanding of learning, the optimization of the learning environment, and evidence-based pedagogical action (Ferguson, 2012). The results also indicate that the impact of teachers' beliefs on their LA-informed actions is a critical area for future research. Specifically, how can LA dashboards support teachers to take pedagogical actions that reflect both the theoretical framework used to develop the LA and their teaching pedagogy?

Taken together, the findings resonate with research showing that developing LA dashboards that are interpretable and actionable requires incorporating teachers' beliefs and dispositions (Rodríguez-Triana, Prieto, Martínez-Monés, et al., 2018; Prieto et al., 2018; Wise & Vytasek, 2017). Furthermore, the results support the shift from "one-size-fits-all" LA research and development to creating design solutions that are developed in partnership with teachers and that can accommodate teachers' diverse teaching pedagogies, which ultimately guide their LA-informed actions.

CHAPTER 6 - SUMMARY AND DISCUSSION

Summary

This dissertation project represents a new phase learning analytics (LA) and dashboard research and development. The project extends efforts towards developing LA based on *learning-congruent data*, data from learning design elements that align with a learning theory and reflect students' developing ideas, rather than on learning-adjacent data (e.g. clickstream data), which lack such alignment. The multiple studies conducted in this project were organized in two phases. Phase 1 focused on KI-based learning design development and evaluation (Studies 1-3) and Phase 2 focused on KI-based LA and teacher dashboard development and evaluation (Studies 4 5)

I conjectured that when analyzed in ways that (a) bring knowledge integration into focus and (b) align with science education standards, learning-congruent data can function as viable proxies for student learning. I further conjectured that LA based on learning-congruent data and aligned with a theory-grounded learning design can serve as the bases for an LA dashboard that when designed according to EDS principles and in alignment with the co-designed WISE photosynthesis unit can provide teachers with actionable insight for supporting the desired student learning. These conjectures were evaluated in the context of middle school science instruction. Within this context, my overall goal for the project was to support teachers of diverse experiences, backgrounds, and teaching practices to understand their students' progress in developing integrated knowledge of energy and matter transformation during photosynthesis and to take evidence-based pedagogical actions to further support their students' integrated, three-dimensional learning.

Phase 1 - Developing and Evaluating a KI-based Learning Design

Study 1 - Mechanistic Photosynthesis Animation Design. In Study 1, I used research-based design principles for developing integrated knowledge via mechanistic reasoning about energy to extend the success of the photosynthesis animation developed by Ryoo and Linn (2012) towards supporting students to construct a scientific explanation of the role of photosynthesis in the cycling of matter and flow of energy in and out of organisms (NGSS performance expectation, MS-LS1-6). I conjectured that if students were supported to understand the mechanism of photosynthesis, then they could develop and demonstrate the integrated knowledge called for by this performance expectation.

The primary finding from this study was that the selected design principles and the decisions made to implement them led to the creation of a mechanistic photosynthesis animation that was accessible to middle school students.

Study 2 - Mechanistic Photosynthesis Animation Classroom Evaluation. In Study 2, I used research-based instructional scaffolding principles for science inquiry to develop instructional supports for student engagement with the Mechanistic Photosynthesis Animation designed in Study 1. I conjectured that if students were adequately supported to engage in each of the three aspects of the science inquiry process (i.e. sense-making, process management, and articulation and reflection) then they would be able to make productive use of the Mechanistic Photosynthesis Animation and thereby develop an integrated understanding of the role of photosynthesis in the cycling of matter and flow of energy in and out of organisms (i.e. meet the NGSS performance expectation, MS-LS1-6). My implementation of the instructional scaffolding principles included a series of video clips for each of the four key energy and matter transformation events depicted in the Mechanistic Photosynthesis Animation. The video clips were supplemented with guiding questions that supported students in attending to the mechanism of photosynthesis (i.e. agents and causation patterns).

A key finding from this study was that students developed a mechanistic understanding of energy and matter transformation during photosynthesis irrespective of whether they were provided with descriptive summaries of the four key events and then asked to answer the guiding question in a multiple-choice format or whether they were required to self-generate an answer without receiving descriptive summaries. Another key finding was that developing a mechanistic understanding of how photosynthesis facilitates the cycling of matter and flow of energy in and out of organisms can occur via two distinct learning pathways. One pathway entailed having prior knowledge of both the inputs and outputs of photosynthesis. The other pathway, which was accessible to students both with and without prior knowledge of the inputs and outputs, entailed developing a mechanistic understanding of energy and matter transformation during photosynthesis.

Study 3 - An RPP-based model for redesigning the WISE Photosynthesis unit. In Study 3, I leveraged a researcher-practitioner partnership to redesign the photosynthesis unit used in Studies 1 and 2. I conjectured that by using a co-design model (Roschelle et al., 2006) that leveraged the learning science expertise of researchers and the classroom expertise of teachers that I could develop hybrid (i.e. online and in-person) learning opportunities to support students in each step of the knowledge integration process towards developing an integrated, three-dimensional understanding of the role of photosynthesis in the cycling of matter and flow of energy in and out of organisms (i.e. meeting the NGSS performance expectation, MS-LS1-6).

The major finding from the study was that researcher expertise in supporting students in the distinguishing ideas steps of the KI process helped fill a critical gap in teacher-designed instruction.

Phase 2 - Developing and Evaluating KI-based LA and Teacher Dashboard

Study 4 - Developing a strategy for developing and implementing LA for integrated, three-dimensional knowledge of photosynthesis. In Study 4, I developed and implemented a strategy for creating and presenting LA based on learning-congruent data. The strategy involved the creation and validation of a rubric to measure students' knowledge along each dimension of the NGSS performance expectation, MS-LS1-6, which calls for students to construct a scientific explanation of the role of photosynthesis in the cycling of matter and flow of energy in and out of organisms. The rubric for measuring the SEP dimension of the MS-LS1-6 performance expectation was created using the KI rubric criteria developed in Study 2 which assesses students' integration of key photosynthesis ideas. The rubric for the DCI and CCC dimension was created using the ideas statements found in the MS-LS1-6 Evidence Statement document. I conjectured that while the DCI and CCC dimension were related there was sufficient conceptual distinction that the rubric criteria for each could measure distinct constructs.

The finding that, while moderately correlated, as determined by Spearman's rho, the rubric criteria for the DCI and CCC dimensions were psychometrically valid measures of the two distinct dimensions, as evidenced by low inter-rater reliability (treating the DCI and CCC rubrics as independent "raters"). I termed the validated rubric measuring SEP, DCI, and CCC the "performance expectation (PE) rubric". By using the PE rubric and leveraging machine learning techniques for automatically scoring students responses in real-time, I created LA for the distribution of students' scores across each MS-LS1-6 dimension and presented them in a teacher dashboard, called the Teacher Action Planner (TAP). The TAP was designed according to the principles of educational datastorytelling and embedded in the WISE system to assist teachers in supporting student learning with the co-designed photosynthesis unit from Study 3.

Study 5 - Evaluating the Student Learning Impact of a Learning Analytics Dashboard in a co-designed photosynthesis unit. In Study 5, I evaluated the TAP, developed in Study 4, for its ability to provide teachers with actionable insights for supporting student learning. I conjectured that the LA for students' integrated, three-dimensional knowledge in conjunction with the EDS-aligned design features of the TAP would assist teachers in supporting students to meet the NGSS performance expectation MS-LS1-6.

One key finding was that the alignment of the LA with the unit's learning design and NGSS performance expectations, and the histogram of scores along each NGSS dimension, supported teachers in understanding their students' learning needs toward developing integrated, three-dimensional knowledge about photosynthesis. Another key finding was that while students in the classes of all three participating teachers developed this type of knowledge after completing teachers data-informed instructional interventions, only the students in the class of the teacher whose intervention supported them in each step of the knowledge integration process retained an integrated, three-dimensional knowledge about photosynthesis after completing the unit. A third key finding was that teachers' instructional interventions were heavily influenced by their individual teaching pedagogy, which may or may not have aligned with the learning that was designed for in the unit using the KI framework.

Discussion

Middle School students benefit from learning the mechanism of natural phenomena

The results from Study 2 demonstrate that supporting students to develop a mechanistic understanding of energy and matter transformation in photosynthesis can help them develop both a normative and mechanistic understanding of the role of photosynthesis in the cycling of matter and flow of energy in and out or organisms.

The results indicate that developing a mechanistic understanding is a viable path for students with both high and low prior knowledge to develop a normative and mechanistic understanding of photosynthesis I contend that this path reflects a learning progression worth incorporating into middle school science curricula, especially for curricula that are aligned to science reform standards like NGSS, that call for the development of integrated and transdisciplinary science knowledge (National Research Council, 2012). Moreover, the finding that students who knew both the inputs and outputs of photosynthesis were more likely to develop a normative and mechanistic understanding of photosynthesis from engagement with Mechanistic Photosynthesis Animation even without additional scaffolding suggests that supporting students in elementary to arrive in middle school with this knowledge can position them to develop a sophisticated understanding of energy and matter transformation during photosynthesis, and perhaps understand other complex science ideas.

These results can, at least in part, be attributed to the research-based principles used to design the mechanistic animation and associated instructional scaffolds. As such, they provide evidence that the principles provide effective guidance for how to support middle school students in developing integrated, three-dimensional knowledge of complex science concepts. The specific implementation of the scaffolding design principles used in Study 2 represent a viable strategy for converting open educational resources into productive learning resources for developing integrated and mechanistic understanding of complex science ideas. This is a strategy that can guide other education researchers and curriculum developers in creating effective learning resources for science students, especially at the middle school level.

Although this study focused on biology, the complex ideas that students were able to learn cut across other science disciplines, like chemistry and physics. Other middle school topics on macro-events that may benefit from animations of their molecular-level transformations include cell respiration, motion and friction, and climate change.

Co-designed units support teachers in taking LA-informed pedagogical action

The primary goal for LA in supporting classroom instruction is to provide teachers with actionable insight (Ferguson, 2012; Jørnø & Gynther, 2018). However, if teachers are not positioned to take action towards optimizing student learning, which often entails customizing the learning design, then the improvement in student learning outcomes sought by the employment of LA can be short-circuited. The results of Study 3 demonstrate that leveraging the RPP model to position teachers in the agentic role of curriculum co-designers enables them to take evidence-based pedagogical action towards supporting student learning both before (Study 3 results) and during instruction (Study 5 results). While the teachers expressed that the LA dashboard helped them understand their students' learning needs, the Study 5 result that most students were not adequately supported by teachers' pedagogical actions suggests that redesigns of the LA dashboard may be warranted. One avenue of redesign could be to include in the dashboard a complete representation of the learning design (Hernández-Leo et al., 2019; Persico & Pozzi, 2015). Other studies have shown that deep knowledge of the learning design is essential for knowing how to take actions in response to the analytics (Rodríguez-Triana, Prieto, Martinez-Mones, et al., 2018; Wiley et al., 2020). The inclusion of a complete representation of the learning design may provide teachers with the necessary insight into the design intent of the curriculum elements needed to support them in knowing how to effectively leverage those elements in their curriculum customizations.

LA based on learning-congruent data function methodologically to investigate integrated, three-dimensional knowledge and support pedagogical action

The Study 5 results provide empirical evidence for the value and importance of grounding all aspects of developing and evaluating LA for learning design in theory (Reimann, 2016). Leveraging learning theory allowed me to develop LA based on learning-congruent data for understanding integrated, three-dimensional knowledge. Specifically, the results from Study 5 indicate that providing teachers with subscores related to students' learning progress along each dimension of a performance expectation supports them in taking evidence-based pedagogical actions, such as customization the learning design. Providing teachers with all three scores together seemed to function as a reminder to them that while students might have robust knowledge on one dimension, they may need additional support related to different dimension. Additionally, the three dimension scores seemed to allow teachers to inquiry into student learning (Mor et al., 2015) with a fine-toothed comb, examining the relationship between students integrated understanding (i.e. their KI score) and their knowledge of particular ideas and concepts targeted by the learning design or science standards (i.e. their DCI and CCC scores). Implicit in the presentation of the scores are numerous permutations associated with student learning progress; the LA dashboard was designed to support teachers in addressing 7 of these permutations. Traditional LA would present teachers with the data analysis and leave them unassisted to explore this complexity. However, since the LA dashboard was designed using the EDS principles it was able to guide teachers in not only how to make sense of the analysis but also how to take focused action to address the revealed student learning needs. In this way the LA dashboard, with its presentation of learning-congruent data (i.e. students' scores/progress along each dimension of the targeted performance expectation), functioned as a methodology to explore student learning. Therefore, developing LA and teacher dashboards using the strategies described in Study 4 positions teachers as both curriculum co-designers and education researchers.

The Study 5 finding that teachers' LA-informed actions were heavily influenced by their pedagogy resonates with research showing that developing LA dashboards that are interpretable and actionable requires incorporating teachers' beliefs and dispositions (Rodríguez-Triana, Prieto, Martinez-Mones, et al., 2018; Prieto et al., 2018; Wise & Vytasek, 2017).

Limitations

While the studies in this dissertation project yielded meaningful findings, there are several limitations to consider. One limitation is the discontinuity in the design of the photosynthesis unit used in Phase 1 versus the unit used in Phase 2. While many items were the exact same or substantively similar, the Mechanistic Photosynthesis Animation and instructional supports were revised from the first to the second iteration of the unit. Although these revisions generated aesthetically and functionally different features, they were developed in accordance with the same design principles. Nevertheless, some revisions may have made the unit overall more effective and thus have a confounding effect on the results reported in Study 2.

A second limitation, also related to the Study 2 results, is the relatively small sample size. Having a small sample size caused the explanatory models to have wide confidence intervals associated with the statistically significant factors in the explanatory models produced in Study 2 (e.g. knowing photosynthesis inputs and outputs as an explanation of students' understanding of the role of photosynthesis). With such wide intervals, I could only comment on the statistical significance of the factors and not their precision of the found effect.

A third limitation is the reliance on the socioconstructivist Knowledge Integration framework to ground the learning design and LA. while the socioconstructivist perspective highlights the importance of students generating knowledge and understands knowledge as embedded in social discourse, other learning theories emphasize different aspects that may be similarly productive in advancing what is known about how people learn. For example, connectivism positions technology as integral to the learning process and may be a perspective that proves particularly productive in current times that are characterized by rapid advances in technology and new technological possibilities (Joksimovic et al., 2014).

A fourth limitation is the particular way the KI framework was applied in this study, namely the focus on the concept of normative ideas. While the goal of the LA was to support teachers in attending to student ideas, the LA was designed to support attention to ideas that were in alignment with those expressed in the NGSS evidence statement and other ideas reflecting the consensus of the current science community. Since the ideas expressed by the current science standards and science community have their origin in Eurocentric ideologies and epistemologies ((Aikenhead et al., 2006; ?, ?)), student ideas that did not align or conform to that perspective may not have been supported. Future LA and dashboard development are needed to support teachers in expanding students' sense-making efforts (?, ?) and helping students to reconcile all their ideas towards developing integrated knowledge (Linn et al., 2003). Further, the dashboard can be developed to support teachers in accepting and integrating various perspectives and epistemologies that exist in their classrooms to promote inclusive science instruction (Bang & Marin, 2015) that not only helps students to integrate their ideas to form coherent understanding, but also helps them to become critical thinkers. As critical thinkers they can contrast and evaluate different perspectives, create arguments to support their position, and accept that there are often multiple solutions to problems. Doing so would be a more faithful application of the KI framework (Linn & Eylon, 2011).

Implications

Proposals and Future Research.

TAP redesigns. The Study 5 finding that students experience long-term learning gains when their teacher made instructional interventions that aligned with the complete cycle of the underlying KI pedagogical framework suggests that supporting such actions in the LA dashboard is a worthwhile pursuit. Indeed progress has already been made to redesign the Recommended Action section of the TAP to highlight the alignment of the recommendation to the KI framework (Figure 23). During a recent WISE teacher professional development workshop, teachers expressed a preference for this revised design (unpublished data). However, further research is needed to evaluate the effectiveness of this strategy for supporting more students to develop integrated, three-dimensional knowledge.

To extend the methodological use of the LA, the TAP has been redesigned to present the initial and reflection analytics in the same display. The design iteration used in Study 5 created two different TAP reports accessible by clicking different icon tiles (Figure 22). Combining the histograms for these timepoints into one display would allow teachers to quickly evaluate the impact of their instructional interventions. By evaluating the effectiveness of their current pedagogical actions, teachers could gain insight not only into how to better support student learning but also into how to improve their instructional practices. Such outcomes would provide evidence for the educative nature of the TAP and open new areas of research in the field of teacher education and professional development.

Additionally, future research should explore extending the TAP recommendations (and LA) directly to students as a strategy for supporting self-directed learning. Recent research suggests value in supporting students to optimize their own learning (Buckingham Shum et al., 2019). Although these studies involved older students, it is worth investigating how to support younger students in effectively using LA to guide their own learning.

Additionally, the Study 5 finding that the LA motivated Teachers 1 and 2 to further inquire into student thinking by reading their students' written responses, which was a primary goal for the TAP design, suggests that facilitating this action directly through the TAP may be a valuable

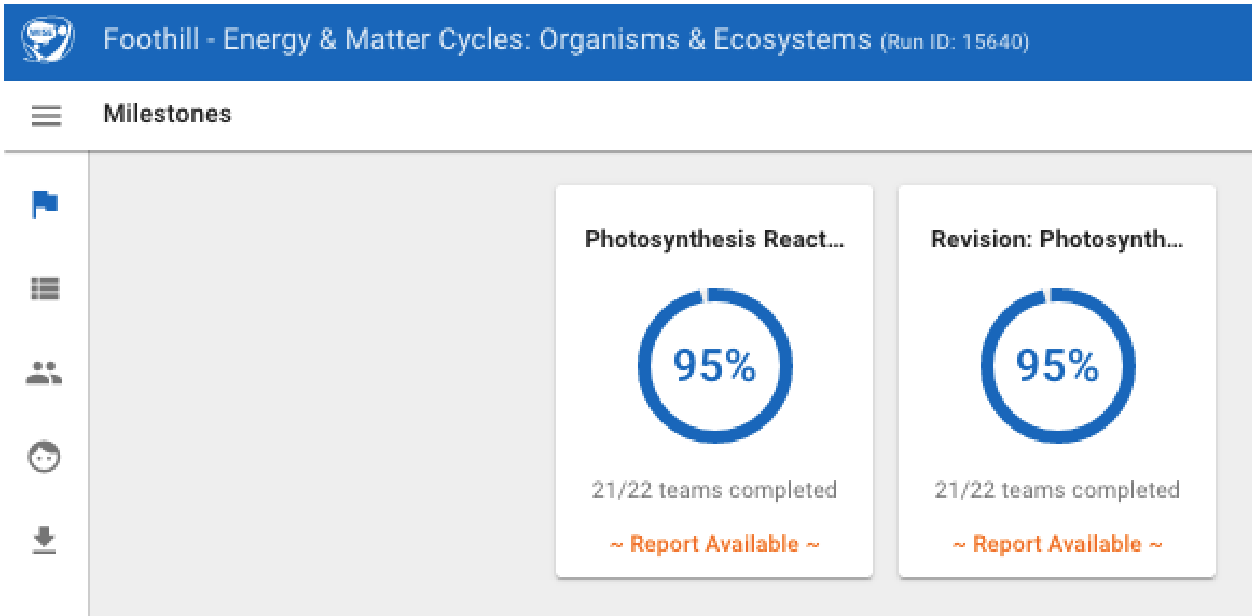


Figure 22: Screenshot of the separate Initial and Reflection TAP reports accessible via the Teacher Grading Tool interface

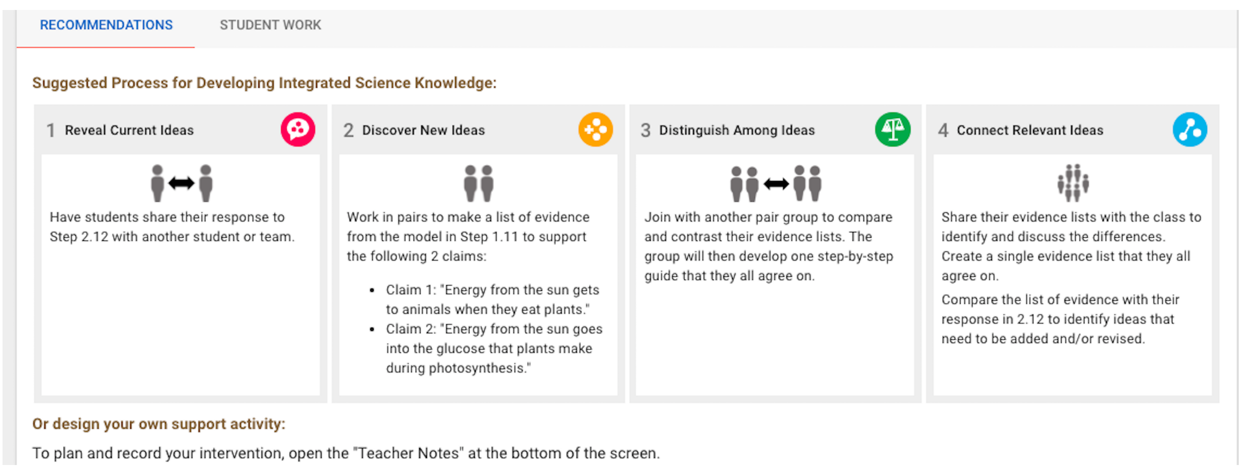


Figure 23: Redesigned Recommended Action section of the TAP. This is an example of the recommended action for the data scenario of low scores across all three NGSS dimensions. The recommended activity is presented to highlight its alignment to the KI process. The redesigned section also includes a statement acknowledging teachers' option to create their own pedagogical action, encouraging them to do so in the WISE-embedded Teacher Notebook.

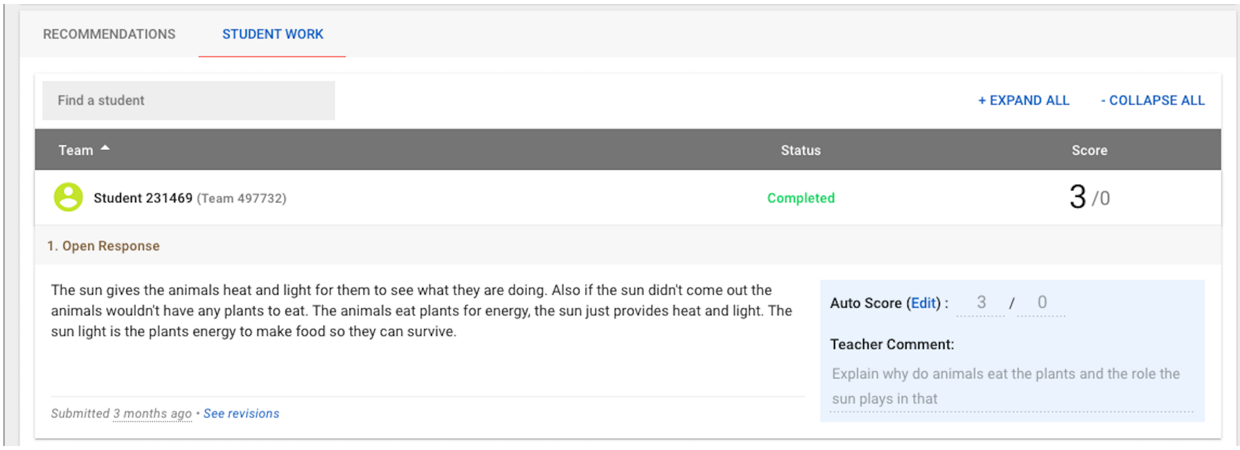


Figure 24: Student Work tab in the Recommended Action section of the TAP. The Student Work tab presents a student roster that includes their written responses to the linked assessment item and sortable autoscores.

redesign. Progress has also been made on this idea. Specifically, a tab to access student work and the corresponding KI scores has been added to the Recommended Action section (Figure 24). This redesign also allows teachers to quickly toggle between TAP and individual student's responses and to sort student responses by score. The sort by score option supports teachers in identifying patterns in the ideas expressed by students at the same score level in a relative short amount of time. Additional research is needed to determine if this increased accessibility and functionality will encourage teacher who otherwise would not read through students' written response (e.g. Teacher 3 from Study 5) to do so and create instructional interventions based on those responses.

Insight for Developing Educative Analytics of Learning for Teachers to Promote Action and Coherent Knowledge. In Study 5, teachers' pedagogical actions were based both on the insight mediated by the LA and on their own pedagogy, which may or may not have aligned with the learning science research reflected in the TAP. This is an important finding because it highlights the need for LA (and their associated dashboards) that support teachers in taking up ideas based on learning science research, especially when those ideas run counter to their pedagogy. Put differently, research aimed at developing both actionable and educative LA is a priority for the next phase of LA development.

Utilizing RPPs in the LA development strategy may facilitate the uptake and exchange of ideas that is necessary for the success of any educative teaching resource (Davis et al., 2017). Based on the strategies used in this dissertation project and the project findings, I propose the Insight for Developing Educative Analytics of Learning for Teachers to Promote Action and Coherent Knowledge (IDEAL TPACK) framework. This framework consists of 3 principles:

1. Co-design with all stakeholders

2. Synergize the learning design cycle and the LA design process

3. Incorporate research-based pedagogical theories to guide iterative LA design and implementation.

The IDEAL TPACK framework is an extension of my previously proposed T-GLADE framework (Wiley et al., 2020), which offered principles for how to leverage theory in the development and evaluation of LA. Many of the principles of the T-GLADE framework are reflected in Principle 3 of the IDEAL TPACK framework. Thus, IDEAL TPACK represents a more comprehensive set of principles for developing actionable (and educative) LA.

IDEAL TPACK Principle 1: Co-design with all stakeholders. The primary objective for co-designing with all stakeholders is to facilitate the exchange of expertise and development of a mutual understanding of each stakeholder's priorities, values, and constraints. In other words, during the LA design process, the voices and expertise of all stakeholders should be considered and leveraged, respectively.

However, facilitating stakeholder dialogue, while crucial for the success of LA implementation, can be challenging. In some cases, this challenge can be managed by careful planning to permit meetings in which all stakeholders can engage synchronously in time and/or space. In other cases, stakeholder meetings can occur asynchronously through communication media, whether digital or analog. The stakeholder forms described by (?, ?) can support such inter-stakeholder communication, as they guide both the content of information exchange and the sequence of stakeholders' responses.

As previously mentioned, RPPs can support this exchange of expertise and ideas. The KI-based co-design model described in Study 3 provides an illustration. During the customization workshop, which proceeded according to the KI process, stakeholders' ideas were elishortcited and made visible for exploration. Given the diversity of expertise and perspectives amongst the stakeholders, this elicitation functioned to provide all the stakeholders with new ideas to distinguish. Distinguishing amongst all the ideas was accomplished collaboratively, with stakeholders aiming to identify the ideas that would be help them achieve the agreed upon design goals. Once identified as productive for meeting the design goals, the stakeholders worked together to integrate and implement their ideas, which they successfully did.

Although students were not included as co-designers in the Study 3 customization workshop, their inclusion in the design process for developing the Mechanistic Photosynthesis Animation provides an example of the value of co-designing with students. Specifically, students' expertise informed a redesign of the animation that made it accessible for our target middle school audience.

In the development of LA that assist teachers to take actions that support students in developing coherent (i.e. integrated) knowledge, students' expertise could inform the selection assessment items that more accurately capture their developing ideas.

IDEAL TPACK Principle 2: Synergize the learning design cycle and the LA design process. Synergizing the process of LA development with the learning design cycle enables LA to support teachers' inquiry into student learning and take evidence-based action (Mor et al., 2015). As described in Study 4, after creating the learning design, specific elements of the design are identified as LA targets (Figure 25, 1). During the orchestration phase (i.e. implementing the learning design), LA are incorporated in the TEL environment. The selected targets generate data to be analyzed by the TEL system, and the resulting LA tool (Figure 25, 2a) function to support

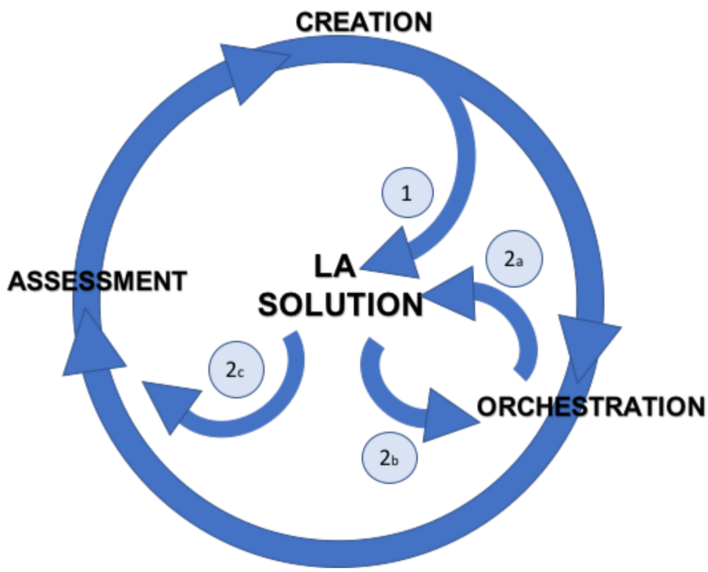


Figure 25: The integration of LA development into the learning design cycle. 1 – LA design: learning design elements selected as targets for LA solution; 2 – LA implementation: a) data from LA targets are analyzed by the LA tool, and the resulting LA informs: b) orchestration, c) and assessment

the understanding of the learning taking place and to inform the pedagogical interventions and orchestration actions needed to optimize student learning (Figure 25, 2b). The LA can also support the assessment phase of the learning design cycle, by providing insight into the effectiveness of the targeted elements in facilitating the desired learning outcomes (Figure 25, 2c).

Achieving this synergy can be complicated by the fact that typically no single stakeholder is responsible for all three elements. In the simplest case, the learning design is developed and orchestrated by a teacher while the LA are designed by researchers and/or system developers. Furthermore, it is not uncommon that each element is developed by a different stakeholder. For example, a system developer may design LA for a learning design that a researcher or instructional designer creates, and a teacher orchestrates. However, the challenges associated with aligning each of the three elements can be mitigated by implementing IDEAL TPACK Principle 1, namely co-designing with all stakeholders. Doing so allows the voices from all relevant stakeholders to be considered in the LA design process, regardless of the configuration of stakeholder responsibilities.

An example of a successful implementation of IDEAL TPACK Principle 2 can been seen in a study by (Wiley et al., 2020). In this study, stakeholders co-designed LA that provided information about students' understanding of how the sun warms the earth. The LA targets were collaboratively identified by researchers and teachers through in-person interstakeholder dialogues. The resulting LA informed a redesign of the online instruction and teacher-mediated classroom activities. The associated LA report (a precursor to the TAP) included a section, called Researchers' Insight, which shared with teachers the researchers' perspective on students' learning needs based on the

LA. All the participating teachers expressed an appreciation for this section as it expanded their perspective on the learning issues and factors. Future design iterations could make the Researchers' Insight section function more educatively. For example, the section could provide teachers with relevant learning science research that gives insight for teachers to both understand and address their students' identified learning need (Davis & Krajcik, 2005).

IDEAL TPACK Principle 3: Incorporate research-based pedagogical theories to guide iterative LA design and implementation. Every aspect of developing LA should be grounded in and guided by a research-based pedagogical theory. Using a theory-grounded development, and implementation strategy allows the LA to be used as a methodological tool for: identifying, understanding, and supporting student learning; optimizing the learning design; and supporting pedagogical action. I take the empirical evidence from this study as validation of this approach.

The main function of a pedagogical theory during the LA design process is to inform the selection of data and extracting metrics that can be associated with higher-order meaningful constructs relevant to the learning design at hand. During LA implementation, a pedagogical theory can also inform how to use the LA to generate actionable insights and inform orchestration actions. Moreover, a pedagogical theory can help to identify the goal towards which learning and its environment are optimized (i.e. learning design redesigns). As such, the theory that guides LA design and implementation should ideally be the same as that used for the learning design.

A potential challenge in meeting IDEAL TPACK Principle 3, particularly when viewed in light of Principle 2 (i.e. synergy between the learning design cycle and LA design process), is when the learning design is created by stakeholders without intimate knowledge of research-based pedagogical theories. Thus, during the LA design process, differences across and amongst stakeholder groups get surfaced, specifically in terms of the values and priorities for how to implement LA. In these situations, the theory can be used as an arbiter. Having a pedagogical theory to guide each aspect of the development process ensures that during the inevitable event of conflicting values and perspectives decisions can be made that safeguard the integrity of the resulting LA. The theory that lays the groundwork for the LA, should ideally be one that aligns with the values of all stakeholders. Stakeholders should attempt to find the common values early in the design process to help guide them towards identifying an appropriate pedagogical theory. Clearly, this process may include compromise, but it avoids the top-down decision for the theory that guides LA.

Final Remarks. With the IDEAL TPACK principles and stakeholders willing to engage in the process, LA can be developed that enrich the teaching and learning context on multiple levels. Teachers can have course specific LA that complement their teaching practices. Students can receive timely and targeted support as they engage in the learning process. Researchers can have data closely aligned to the learning process with which they can further explore and expand theories of learning. System developers can have opportunities to apply and extend analysis techniques to generate analytics that are easily understood and implemented in the classroom context. I invite other researchers to test the robustness and versatility of these principles to guide the development of LA for learning design in other contexts and with different theories and stakeholder groups.

In sum, the findings presented in this dissertation and the IDEAL TPACK framework, raise two promising areas of research for the years to come: 1.) using LA as a methodological tool to explore teaching and learning, 2.) designing LA that can be an educative resource for teachers. Whether and how LA dashboards can be developed to influence teachers' philosophy for teaching needs further exploration. However, if such LA can be developed, this could bridge the gap between theory and classroom action and open new frontiers for supporting teacher education, pre-service and in-service teacher training, as well as for supporting students during in-person and remote learning contexts.

Statement of contribution. The results of my dissertation project contribute to the area of NGSS curriculum assessment by providing new strategies for developing and validating rubrics to measure NGSS performance expectations. They also contribute to the fields of learning analytics and teacher professional development, as they provide insight for how to support teachers to use, interpret, and respond to LA based on learning-congruent data within TEL environments. In sum, my dissertation project advances the knowledge base for teaching, learning, and assessment in TEL environments.

REFERENCES

Abrams, E., & Southerland, S. (2001). The how's and why's of biological change: How learners neglect physical mechanisms in their search for meaning. *International Journal of Science Education*, *23*(12), 1271–1281. doi: 10.1080/09500690110038558

Achieve. (2013). *Criteria for procuring and evaluating high-quality and aligned summative science assessments.* Retrieved 2016-10-10, from `https://www.nextgenscience.org/sites/default/files/evidence_statement/black_white/MS-LS1-6%20Evidence%20Statements%20June%202015%20asterisks.pdf`

Achieve. (2018). *Criteria for procuring and evaluating high-quality and aligned summative science assessments.* Retrieved 2018-05-28, from `https://www.nextgenscience.org/sites/default/files/Criteria03202018.pdf`

Aikenhead, G., Calabrese, A. B., & Chinn, P. W. U. (2006). Forum: Toward a politics of place-based science education. *Cultural Studies of Science Education*, *1*(2), 403–416. doi: 10.1007/s11422-006-9015-z

Alhadad, S. (2018). Visualizing Data to Support Judgement, Inference, and Decision Making in Learning Analytics: Insights from Cognitive Psychology and Visualization Science. *Journal of Learning Analytics*, *5*(2), 60–85. doi: 10.18608/jla.2018.52.5

Alverson, C. Y., & Yamamoto, S. H. (2016). Educational Decision Making With Visual Data and Graphical Interpretation: Assessing the Effects of User Preference and Accuracy. *SAGE Open*, *6*(4), 215824401667829. doi: 10.1177/2158244016678290

Anderson, C. W., Sheldon, T. H., & Dubay, J. (1990). The effects of instruction on college nonmajors' conceptions of respiration and photosynthesis. *Journal of Research in Science Teaching*, *27*(8), 761–776. doi: 10.1002/tea.3660270806

Asensio-Pérez, J. I., Dimitriadis, Y., Pozzi, F., Hernández-Leo, D., Prieto, L. P., Persico, D., & Villagrá-Sobrino, S. L. (2017). Towards teaching as design: Exploring the interplay between full-lifecycle learning design tooling and teacher professional development. *Computers & Education*, *114*, 92–116. doi: https://doi.org/10.1016/j.compedu.2017.06.011

Baker, R., Xu, D., Park, J., Yu, R., Li, Q., Cung, B., ... Smyth, P. (2020). The benefits and caveats of using clickstream data to understand student self-regulatory behaviors: opening the black box of learning processes. *International Journal of Educational Technology in Higher Education*, *17*(1). doi: 10.1186/s41239-020-00187-1

Bang, M., & Marin, A. (2015). Nature-culture constructs in science learning: Human/non-human agency and intentionality: NATURE-CULTURE CONSTRUCTS IN SCIENCE LEARNING. *Journal of Research in Science Teaching*, *52*(4), 530–544. doi: 10.1002/tea.21204

Bendel, R. B., & Afifi, A. A. (1977). Comparison of stopping rules in forward "stepwise" regression. *Journal of the American Statistical Association*, *72*(357), 46–53. doi: 10.1080/01621459.1977.10479905

Bergner, Y., Gray, G., & Lang, C. (2018). What Does Methodology Mean for Learning Analytics? *Journal of Learning Analytics*, *5*(2), 1–8. doi: 10.18608/jla.2018.52.1

Bridwell, L. S. (1980). Revising strategies in twelfth grade students' transactional writing. *Re-*

search in the Teaching of English, 197–222.

Buckingham Shum, S., Ferguson, R., & Martinez-Maldonado, R. (2019). Human-centred learning analytics. *Journal of Learning Analytics*, *6*(2), 1–9.

Chi, M. T. H. (2005). Commonsense conceptions of emergent processes: Why some misconceptions are robust. *Journal of the Learning Sciences*, *14*(2), 161–199. doi: 10.1207/s15327809jls1402_1

Chi, M. T. H. (2008). Three Types of Conceptual Change: Belief Revision, Mental Model Transformation, and Categorical Shift. In S. Vosniadou (Ed.), *Handbook of research on conceptual change* (pp. 61–82). Hillsdale, NJ: Erlbaum.

Clark, D., & Linn, M. (2013). *The knowledge integration perspective: Connections across research and education*. doi: 10.4324/9780203154472

Clark, R. E., & Feldon, D. F. (2014). Ten common but questionable principles of multimedia learning..

Clow, D. (2012). The learning analytics cycle: closing the loop effectively. In *Proceedings of the 2nd International Conference on Learning Analytics and Knowledge - LAK '12* (p. 134). Vancouver, British Columbia, Canada: ACM Press. doi: 10.1145/2330601.2330636

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. doi: 10.1002/tea.20440

Collins, A. (1992). Toward a Design Science of Education. In E. Scanlon & T. O'Shea (Eds.), *New Directions in Educational Technology* (pp. 15–22). Berlin, Heidelberg: Springer Berlin Heidelberg. doi: 10.1007/978-3-642-77750-9_2

Crawford, L., Lloyd, S., & Knoth, K. (2008). Analysis of student revisions on a state writing test. *Assessment for Effective Intervention*, *33*(2), 108–119. doi: 10.1177/1534508407311403

Davis, E. A., & Krajcik, J. S. (2005). Designing Educative Curriculum Materials to Promote Teacher Learning. *Educational Researcher*, *34*(3), 3–14. doi: 10.3102/0013189X034003003

Davis, E. A., Palincsar, A. S., Smith, P. S., Arias, A. M., & Kademian, S. M. (2017). Educative curriculum materials: Uptake, impact, and implications for research and design. *Educational Researcher*, *46*(6), 293–304. doi: 10.3102/0013189x17727502

Dawson, S., Gašević, D., Siemens, G., & Joksimovic, S. (2014). Current state and future trends: a citation network analysis of the learning analytics field. In *Proceedins of the Fourth International Conference on Learning Analytics And Knowledge - LAK '14* (pp. 231–240). Indianapolis, Indiana: ACM Press. doi: 10.1145/2567574.2567585

de Jong, T. (2019). Moving towards engaged learning in STEM domains; there is no simple answer, but clearly a road ahead. *Journal of Computer Assisted Learning*, *35*(2), 153–167. doi: 10.1111/jcal.12337

Disessa, A. (2008). A bird's-eye view of the "pieces" vs. "coherence" controversy (from the "pieces" side of the fence). *International Handbook of Research on Conceptual Change*, 35–60.

Duit, R. (1987). Should energy be illustrated as something quasi-material? *International Journal of Science Education*, *9*(2), 139–145. doi: 10.1080/0950069870090202

Duncan, R. G., & Rivet, A. E. (2013). Science Learning Progressions. *Science*, *339*(6118), 396–397. doi: 10.1126/science.1228692

Echeverria, V., Martinez-Maldonado, R., Granda, R., Chiluiza, K., Conati, C., & Shum, S. B. (2018). Driving data storytelling from learning design. In *Proceedings of the 8th International Conference on Learning Analytics and Knowledge - LAK '18* (pp. 131–140). Sydney, New South Wales, Australia: ACM Press. doi: 10.1145/3170358.3170380

Echeverria, V., Martinez-Maldonaldo, R., Buckingham Shum, S., Chiluiza, K., Granda, R., & Conati, C. (2018). Exploratory versus Explanatory Visual Learning Analytics: Driving Teachers' Attention through Educational Data Storytelling. *Journal of Learning Analytics*, *5*(3), 72–97. doi: 10.18608/jla.2018.53.6

Feng, M., Krumm, A. E., Bowers, A. J., & Podkul, T. (2016). Elaborating data intensive research methods through researcher-practitioner partnerships. In *Proceedings of the Sixth International Conference on Learning Analytics & Knowledge - LAK '16* (pp. 540–541). Edinburgh, United Kingdom: ACM Press. doi: 10.1145/2883851.2883908

Ferguson, R. (2012). Learning analytics: drivers, developments and challenges. *International Journal of Technology Enhanced Learning*, *4*(5/6), 304. doi: 10.1504/IJTEL.2012.051816

Fischer, F., Kollar, I., Stegmann, K., & Wecker, C. (2013). Toward a Script Theory of Guidance in Computer-Supported Collaborative Learning. *Educational Psychologist*, *48*(1), 56–66. doi: 10.1080/00461520.2012.748005

Fleiss, J. L., Levin, B., & Paik, M. C. (2003). The Measurement of Interrater Agreement. In *Statistical methods for rates and proportions* (3rd ed ed., pp. 598–626). Hoboken, N.J: J. Wiley.

Friend Wise, A., & Jung, Y. (2019). Teaching with analytics: Towards a situated model of instructional decision-making. *Journal of Learning Analytics*, *6*(2), 53–69. doi: 10.18608/jla.2019.62.4

Fuchs, C., & Diamantopoulos, A. (2009). Using single-item measures for construct measurement in management research: Conceptual issues and application guidelines. *Die Betriebswirtschaft*, *69*, 195–210.

Gašević, D., Dawson, S., & Siemens, G. (2015). Let's not forget: Learning analytics are about learning. *TechTrends*, *59*(1), 64–71. doi: 10.1007/s11528-014-0822-x

Gašević, D., Kovanović, V., & Joksimović, S. (2017). Piecing the learning analytics puzzle: a consolidated model of a field of research and practice. *Learning: Research and Practice*, *3*(1), 63–78. doi: 10.1080/23735082.2017.1286142

Gerard, L. F., & Linn, M. C. (2016). Using Automated Scores of Student Essays to Support Teacher Guidance in Classroom Inquiry. *Journal of Science Teacher Education*, *27*(1), 111–129. doi: 10.1007/s10972-016-9455-6

Gerard, L. F., Varma, K., Corliss, S. B., & Linn, M. C. (2011). Professional Development for Technology-Enhanced Inquiry Science. *Review of Educational Research*, *81*(3), 408–448. doi: 10.3102/0034654311415121

Goodyear, P., & Dimitriadis, Y. (2013). In medias res: Reframing design for learning. *Research in Learning Technology*, *21*. doi: 10.3402/rlt.v21i0.19909

Grotzer, T. A. (2003). Learning to Understand the Forms of Causality Implicit in Scientifically Accepted Explanations. *Studies in Science Education*, *39*(1), 1–74. doi: 10.1080/03057260308560195

Haklev, S., Faucon, L. P., Hadzilacos, T., & Dillenbourg, P. (2017). Frog: rapid prototyping of collaborative learning scenarios. In *Ec-tel.*

Hernández-Leo, D., Martinez-Maldonado, R., Pardo, A., Muñoz-Cristóbal, J. A., & Rodríguez-Triana, M. J. (2019). Analytics for learning design: A layered framework and tools: Analytics layers for learning design. *British Journal of Educational Technology*, *50*(1), 139–152. doi: 10.1111/bjet.12645

Hmelo-Silver, C. E., & Pfeffer, M. G. (2004). Comparing expert and novice understanding of a complex system from the perspective of structures, behaviors, and functions. *Cognitive Science*, *28*(1), 127–138. doi: 10.1207/s15516709cog2801_7

Holstein, K., Hong, G., Tegene, M., McLaren, B. M., & Aleven, V. (2018). The classroom as a dashboard: co-designing wearable cognitive augmentation for K-12 teachers. In *Proceedings of the 8th International Conference on Learning Analytics and Knowledge - LAK '18* (pp. 79–88). Sydney, New South Wales, Australia: ACM Press. doi: 10.1145/3170358.3170377

Holstein, K., McLaren, B. M., & Aleven, V. (2017). Intelligent tutors as teachers' aides: exploring teacher needs for real-time analytics in blended classrooms. In *Proceedings of the Seventh International Learning Analytics & Knowledge Conference on - LAK '17* (pp. 257–266). Vancouver, British Columbia, Canada: ACM Press. doi: 10.1145/3027385.3027451

Höffler, T. N., & Leutner, D. (2007). Instructional animation versus static pictures: A meta-analysis. *Learning and Instruction*, *17*(6), 722–738. doi: 10.1016/j.learninstruc.2007.09.013

Jin, H., & Anderson, C. W. (2012). A learning progression for energy in socio-ecological systems. *Journal of Research in Science Teaching*, *49*(9), 1149–1180. doi: 10.1002/tea.21051

Joksimovic, S., Gasevic, D., & Hatala, M. (2014). Learning analytics for networked learning models. *Journal of Learning Analytics*, *1*(3), 195–198. doi: 10.18608/jla.2014.13.20

Jørnø, R. L., & Gynther, K. (2018). What Constitutes an "Actionable Insight" in Learning Analytics? *Journal of Learning Analytics*, *5*(3), 198–221. doi: 10.18608/jla.2018.53.13

Kalyuga, S., Ayres, P., Chandler, P., & Sweller, J. (2003). The expertise reversal effect. *Educational Psychologist*, *38*(1), 23–31. doi: 10.1207/s15326985ep3801_4

Keleş, E., & Kefeli, P. (2010). Determination of student misconceptions in "photosynthesis and respiration" unit and correcting them with the help of cai material. *Procedia - Social and Behavioral Sciences*, *2*(2), 3111–3118. doi: 10.1016/j.sbspro.2010.03.474

Kesidou, S., & Roseman, J. E. (2002). How well do middle school science programs measure up? Findings from Project 2061's curriculum review. *Journal of Research in Science Teaching*, *39*(6), 522–549. doi: 10.1002/tea.10035

Kok, A. (2009). Understanding the Technology Enhanced Learning Environments from A Cognitive Perspective. *International Education Studies*, *2*(4), p3. doi: 10.5539/ies.v2n4p3

Kozma, R. B., & Russell, J. (1997). Multimedia and understanding: Expert and novice responses to different representations of chemical phenomena. *Journal of Research in Science Teaching*, *34*(9), 949–968. doi: 10.1002/(sici)1098-2736(199711)34:9<949::aid-tea7>3.0.co;2-u

Krajcik, J., & Delen, I. (2017). The Benefits and Limitations of Educative Curriculum Materials.

Journal of Science Teacher Education, *28*(1), 1–10. doi: 10.1080/1046560X.2017.1279470

Krist, C., Schwarz, C. V., & Reiser, B. J. (2018). Identifying essential epistemic heuristics for guiding mechanistic reasoning in science learning. *Journal of the Learning Sciences*, *28*(2), 160–205. doi: 10.1080/10508406.2018.1510404

Lave, J. (1996). Teaching, as Learning, in Practice. *Mind, Culture, and Activity*, *3*(3), 149–164. doi: 10.1207/s15327884mca0303_2

Leary, H., Severance, S., Penuel, W. R., Quigley, D., Sumner, T., & Devaul, H. (2016). Designing a Deeply Digital Science Curriculum: Supporting Teacher Learning and Implementation with Organizing Technologies. *Journal of Science Teacher Education*, *27*(1), 61–77. doi: 10.1007/s10972-016-9452-9

Lee, H.-S., & Liu, O. L. (2009). Assessing learning progression of energy concepts across middle school grades: The knowledge integration perspective. *Science Education*, *94*(4), 665–688. doi: 10.1002/sce.20382

Li, Q., Baker, R., & Warschauer, M. (2020). Using clickstream data to measure, understand, and support self-regulated learning in online courses. *The Internet and Higher Education*, *45*, 100727. doi: 10.1016/j.iheduc.2020.100727

Linn, M. C. (2006). WISE teachers: Using technology and inquiry for science instruction. In E. A. Ashburn & R. E. Floden (Eds.), *Meaning Learning Using Technology: What Educators Need to Know* (pp. 45–69). New York: Teachers College Press.

Linn, M. C., Chang, H.-Y., Chiu, J. L., Zhang, Z. H., & McElhaney, K. W. (2011). Can desirable difficulties overcome deceptive clarity in scientific visualizations? In A. S. Benjamin (Ed.), *Successful remembering and successful forgetting: A festschrift in honor of Robert A. Bjork* (pp. 235–258). New York, NY: Psychology Press.

Linn, M. C., Clark, D., & Slotta, J. D. (2003). Wise design for knowledge integration. *Science Education*, *87*(4), 517–538. doi: 10.1002/sce.10086

Linn, M. C., & Eylon, B.-S. (2011). *Science learning and instruction: taking advantage of technology to promote knowledge integration*. New York: Routledge. (OCLC: ocn176946367)

Liu, O. L., Lee, H.-S., Hofstetter, C., & Linn, M. (2008). Assessing knowledge integration in science: Construct, measures, and evidence. *Educational Assessment*, *13*(1), 33–55. doi: 10.1080/10627190801968224

Liu, O. L., Lee, H.-S., & Linn, M. C. (2011). Measuring knowledge integration: Validation of four-year assessments. *Journal of Research in Science Teaching*, *48*(9), 1079–1107. doi: 10.1002/tea.20441

Liu, O. L., Rios, J. A., Heilman, M., Gerard, L., & Linn, M. C. (2016). Validation of automated scoring of science assessments: AUTOMATED SCORING OF SCIENCE ASSESSMENT. *Journal of Research in Science Teaching*, *53*(2), 215–233. doi: 10.1002/tea.21299

Lockyer, L., Heathcote, E., & Dawson, S. (2013). Informing Pedagogical Action: Aligning Learning Analytics With Learning Design. *American Behavioral Scientist*, *57*(10), 1439–1459. doi: 10.1177/0002764213479367

Mangaroska, K., & Giannakos, M. N. (2018). Learning analytics for learning design: A systematic literature review of analytics-driven design to enhance learning. *IEEE Transactions on Learning Technologies*, *12*(4), 1–1. doi: 10.1109/TLT.2018.2868673

Marmaroti, P., & Galanopoulou, D. (2006). Pupils' Understanding of Photosynthesis: A questionnaire for the simultaneous assessment of all aspects. *International Journal of Science Education*, *28*(4), 383–403. doi: 10.1080/09500690500277805

Mayer, R. E., & Moreno, R. (2003). Nine Ways to Reduce Cognitive Load in Multimedia Learning. *Educational Psychologist*, *38*(1), 43–52. doi: 10.1207/S15326985EP3801_6

Means, B., Chen, E., DeBarger, A. H., & Padilla, C. (2011). *Teachers' Ability to Use Data to Inform Instruction: Challenges and Supports* (Technical). Office of Planning, Evaluation, and Policy Department: U.S. Department of Education.

Metz, K. (1997). On the Complex Relation Between Cognitive Developmental Research and Children's Science Curricula. *Review of Educational Research*, *67*(1), 151–163.

Millar, R., University of York, & Department of Educational Studies. (2005). *Teaching about energy*. York: University of York, Department of Educational Studies. (OCLC: 500350958)

Mor, Y., Ferguson, R., & Wasson, B. (2015). Editorial: Learning design, teacher inquiry into student learning and learning analytics: A call for action: Learning design, TISL and learning analytics. *British Journal of Educational Technology*, *46*(2), 221–229. doi: 10.1111/bjet.12273

Murre, J. M. J., & Dros, J. (2015). Replication and Analysis of Ebbinghaus' Forgetting Curve. *PloS One*, *10*(7), e0120644. doi: 10.1371/journal.pone.0120644

National Research Council. (1996). *National science education standards*. National Academies Press. doi: 10.17226/4962

National Research Council. (2012). *A Framework for K-12 Science Education: Practices, Crosscutting Concepts, and Core Ideas*. Washington, D.C.: National Academies Press. doi: 10.17226/13165

National Research Council. (2013). *Next Generation Science Standards: For States, By States*. Washington, D.C.: National Academies Press. doi: 10.17226/18290

Novak, J. D., & Gowin, D. B. (1984). *Learning how to learn*. Cambridge [Cambridgeshire] ; New York: Cambridge University Press.

Ong, F., Bruton, S., California, & California (Eds.). (2000). *Science content standards for California public schools: kindergarten through grade twelve*. Sacramento, CA: Dept. of Education. (OCLC: ocm48001607)

Otero, V. K. (2006). Moving Beyond the "Get it or Don't" Conception of Formative Assessment. *Journal of Teacher Education*, *57*(3), 247–255. doi: 10.1177/0022487105285963

Penuel, W. R., & Gallagher, L. P. (2009). Preparing Teachers to Design Instruction for Deep Understanding in Middle School Earth Science. *Journal of the Learning Sciences*, *18*(4), 461–508. doi: 10.1080/10508400903191904

Persico, D., & Pozzi, F. (2015). Informing learning design with learning analytics to improve teacher inquiry: Informing LD with LA to improve teacher inquiry. *British Journal of Educational Technology*, *46*(2), 230–248. doi: 10.1111/bjet.12207

Prieto, L. P., Rodríguez-Triana, M. J., Martínez-Maldonado, R., Dimitriadis, Y., & Gašević, D. (2018). Orchestrating learning analytics (OrLA): Supporting inter-stakeholder communication about adoption of learning analytics at the classroom level. *Australasian Journal of Educational Technology*, *35*(4). doi: 10.14742/ajet.4314

Quinn, H. R. (2014). A Physicist's Musings on Teaching About Energy. In R. F. Chen et al. (Eds.), *Teaching and Learning of Energy in K – 12 Education* (pp. 15–36). Cham: Springer International Publishing. doi: 10.1007/978-3-319-05017-1_2

Quintana, C., Davis, E. A., Krajcik, J., & Fretz, E. (2004). A Scaffolding Design Framework for Software to Support Science Inquiry. *The Journal of Learning Sciences*, *13*(3), 337– 386.

Reif, F., & Larkin, J. H. (1991). Cognition in scientific and everyday domains: Comparison and learning implications. *Journal of Research in Science Teaching*, *28*(9), 733–760. doi: 10.1002/tea.3660280904

Reimann, P. (2016). Connecting learning analytics with learning research: the role of design-based research. *Learning: Research and Practice*, *2*(2), 130–142. doi: 10.1080/23735082.2016.1210198

Reindl, K. M., White, A. R., Johnson, C., Vender, B., Slator, B. M., & McClean, P. (2015). The Virtual Cell Animation Collection: Tools for Teaching Molecular and Cellular Biology. *PLOS Biology*, *13*(4), e1002118. doi: 10.1371/journal.pbio.1002118

Riordan, B., Bichler, S., Bradford, A., King Chen, J., Wiley, K., Gerard, L., & C. Linn, M. (2020). An empirical investigation of neural methods for content scoring of science explanations. In *Proceedings of the fifteenth workshop on innovative use of nlp for building educational applications* (pp. 135–144). Seattle, WA, USA Online: Association for Computational Linguistics. doi: 10.18653/v1/2020.bea-1.13

Robertson, A. D., Scherr, R. E., & Hammer, D. (Eds.). (2016). *Responsive teaching in science and mathematics*. New York: Routledge, Taylor & Francis Group.

Rodríguez-Triana, M. J., Martínez-Monés, A., Asensio-Pérez, J. I., & Dimitriadis, Y. (2015). Scripting and monitoring meet each other: Aligning learning analytics and learning design to support teachers in orchestrating CSCL situations: Scripting and monitoring meet each other. *British Journal of Educational Technology*, *46*(2), 330–343. doi: 10.1111/bjet.12198

Rodríguez-Triana, M. J., Prieto, L. P., Martinez-Mones, A., Asensio-Perez, J. I., & Dimitriadis, Y. (2018). Monitoring Collaborative Learning Activities: Exploring the Differential Value of Collaborative Flow Patterns for Learning Analytics. In *2018 IEEE 18th International Conference on Advanced Learning Technologies (ICALT)* (pp. 155–159). Mumbai: IEEE. doi: 10.1109/ICALT.2018.00044

Rodríguez-Triana, M. J., Prieto, L. P., Martínez-Monés, A., Asensio-Pérez, J. I., & Dimitriadis, Y. (2018). The teacher in the loop: customizing multimodal learning analytics for blended learning. In *Proceedings of the 8th International Conference on Learning Analytics and Knowledge - LAK '18* (pp. 417–426). Sydney, New South Wales, Australia: ACM Press. doi: 10.1145/3170358.3170364

Roschelle, J., Penuel, W. R., & Shechtman, N. (2006). Co-design of innovations with teachers: Definition and dynamics. In *Proceedings of the 7th international conference on learning sciences* (p. 606–612). International Society of the Learning Sciences.

Roseman, J. E., Herrmann-Abell, C. F., & Koppal, M. (2017). Designing for the Next Generation Science Standards: Educative Curriculum Materials and Measures of Teacher Knowledge. *Journal of Science Teacher Education*, *28*(1), 111–141. doi: 10.1080/1046560X.2016.1277598

Roseman, J. E., Stern, L., & Koppal, M. (2010). A method for analyzing the coherence of high school biology textbooks. *Journal of Research in Science Teaching*, *47*(1), 47–70. doi: 10.1002/tea.20305

Russ, R. S., Scherr, R. E., Hammer, D., & Mikeska, J. (2008). Recognizing mechanistic reasoning in student scientific inquiry: A framework for discourse analysis developed from philosophy of science. *Science Education*, *92*(3), 499–525. doi: 10.1002/sce.20264

Ryoo, K., & Bedell, K. (2017). The effects of visualizations on linguistically diverse students' understanding of energy and matter in life science: THE EFFECTS OF VISUALIZATIONS FOR LINGUISTICALLY DIVERSE STUDENTS. *Journal of Research in Science Teaching*, *54*(10), 1274–1301. doi: 10.1002/tea.21405

Ryoo, K., & Linn, M. C. (2012). Can dynamic visualizations improve middle school students' understanding of energy in photosynthesis? *Journal of Research in Science Teaching*, *49*(2), 218–243. doi: 10.1002/tea.21003

Ryoo, K., & Linn, M. C. (2014). Designing guidance for interpreting dynamic visualizations: Generating versus reading explanations: GUIDANCE FOR INTERPRETING DYNAMIC VISUALIZATIONS. *Journal of Research in Science Teaching*, *51*(2), 147–174. doi: 10 .1002/tea.21128

Sandoval, W. A., & Bell, P. (2004). Design-Based Research Methods for Studying Learning in Context: Introduction. *Educational Psychologist*, *39*(4), 199–201. doi: 10.1207/ s15326985ep3904_1

Schwarz, C., Passmore, C., & Reiser, B. J. (Eds.). (2016). *Helping students make sense of the world using next generation science and engineering practices*. Arlington, Virginia: NSTA Press, National Science Teachers Association.

Schwendimann, B. A., Rodriguez-Triana, M. J., Vozniuk, A., Prieto, L. P., Boroujeni, M. S., Holzer, A., ... Dillenbourg, P. (2017). Perceiving Learning at a Glance: A Systematic Literature Review of Learning Dashboard Research. *IEEE Transactions on Learning Technologies*, *10*(1), 30–41. doi: 10.1109/TLT.2016.2599522

Smith III, J. P., diSessa, A. A., & Roschelle, J. (1994). Misconceptions reconceived: A constructivist analysis of knowledge in transition. *Journal of the Learning Sciences*, *3*(2), 115–163. doi: 10.1207/s15327809jls0302_1

Stern, L., & Roseman, J. E. (2004). Can middle-school science textbooks help students learn important ideas? findings from project 2061's curriculum evaluation study: Life science. *Journal of Research in Science Teaching*, *41*(6), 538–568. doi: 10.1002/tea.20019

Tansomboon, C., Gerard, L. F., Vitale, J. M., & Linn, M. C. (2017). Designing automated guidance to promote productive revision of science explanations. *International Journal of Artificial Intelligence in Education*, *27*(4), 729–757. doi: 10.1007/s40593-017-0145-0

Tissenbaum, M., Lui, M., & Slotta, J. D. (2012). Co-Designing Collaborative Smart Classroom Curriculum for Secondary School Science. *JUCS - Journal of Universal Computer Science*(3). doi: 10.3217/jucs-018-03-0327

Tissenbaum, M., & Slotta, J. D. (2012). Scaffolding a Knowledge Community for High School Physics. In *Proceedings of the 10th internation conference of the Learning Sciences* (p. 9). Sydney, New South Wales, Australia.

van Leeuwen, A. (2015). Learning analytics to support teachers during synchronous CSCL: Balancing between overview and overload. *Journal of Learning Analytics*, *2*(2), 138–162. doi: 10.18608/jla.2015.22.11

van Mil, M. H. W., Boerwinkel, D. J., & Waarlo, A. J. (2013). Modelling Molecular Mechanisms: A Framework of Scientific Reasoning to Construct Molecular-Level Explanations for Cellular Behaviour. *Science & Education*, *22*(1), 93–118. doi: 10.1007/s11191-011-9379-7

van MIL, M. H. W., Postma, P. A., Boerwinkel, D. J., Klaassen, K., & Waarlo, A. J. (2016). Molecular Mechanistic Reasoning: Toward Bridging the Gap Between the Molecular and Cellular Levels in Life Science Education: MOLECULAR MECHANISTIC REASONING. *Science Education*, *100*(3), 517–585. doi: 10.1002/sce.21215

Vatrapu, R., Teplovs, C., Fujita, N., & Bull, S. (2011). Towards visual analytics for teachers' dynamic diagnostic pedagogical decision-making. In *Proceedings of the 1st International Conference on Learning Analytics and Knowledge - LAK '11* (p. 93). Banff, Alberta, Canada: ACM Press. doi: 10.1145/2090116.2090129

Verbert, K., Duval, E., Klerkx, J., Govaerts, S., & Santos, J. L. (2013). Learning Analytics Dashboard Applications. *American Behavioral Scientist*, *57*(10), 1500–1509. doi: 10.1177/0002764213479363

Visintainer, T., & Linn, M. (2015). Sixth-Grade Students' Progress in Understanding the Mechanisms of Global Climate Change. *Journal of Science Education and Technology*, *24*(2-3), 287–310. doi: 10.1007/s10956-014-9538-0

Vitale, J. M., McBride, E., & Linn, M. C. (2016). Distinguishing complex ideas about climate change: knowledge integration vs. specific guidance. *International Journal of Science Education*, *38*(9), 1548–1569. doi: 10.1080/09500693.2016.1198969

Walkoe, J., Wilkerson, M., & Elby, A. (2017). Technology-mediated teacher noticing: A goal for classroom practice, tool design, and professional development. In B. K. Smith, M. Borge, E. Mercier, & K. Y. Lim (Eds.), *12th International Conference for Computer Supported Collaborative Learning: Making a Difference: Prioritizing Equity and Access in CSCL* (Vol. 1, pp. 65–70). Philadelphia, PA.

Watson, P., & Petrie, A. (2010). Method agreement analysis: A review of correct methodology. *Theriogenology*, *73*(9), 1167–1179. doi: 10.1016/j.theriogenology.2010.01.003

Whitaker, D., & Jacobbe, T. (2017). Students' Understanding of Bar Graphs and Histograms: Results From the LOCUS Assessments. *Journal of Statistics Education*, *25*(2), 90–102. doi: 10.1080/10691898.2017.1321974

Wiley, K. J., Bradford, A., & Linn, M. C. (2019). Supporting Collaborative Curriculum Customizations Using the Knowledge Integration Framework. In K. Lund, G. P. Niccolai, E. Lavoue, C. Hmelo-Silver, G. Gweon, & M. Baker (Eds.), *A Wide Lens: Combining Embodied, Enactive, Extended, and Embedded Learning in Collaborative Settings, 13th International Conference on Computer Supported Collaborative Learning* (Vol. 1, pp. 480–487). Lyon, France: International Society of the Learning Sciences (ISLS).

Wiley, K. J., Dimitriadis, Y., Bradford, A., & Linn, M. C. (2020). From theory to action: Developing and evaluating learning analytics for learning design. In *Proceedings of the tenth international conference on learning analytics & knowledge* (pp. 569–578).

Wise, A. F., & Schaffer, D. W. (2015). Why theory matters more than ever in the age of big data. *Journal of Learning Analytics*, *2*(2), 5–13. doi: 10.18608/jla.2015.22.2

Wise, A. F., & Vytasek, J. (2017). Learning Analytics Implementation Design. In C. Lang, G. Siemens, A. Wise, & D. Gasevic (Eds.), *Handbook of Learning Analytics* (First ed., pp. 151–160). Society for Learning Analytics Research (SoLAR). doi: 10.18608/hla17.013

Wise, A. F., Vytasek, J. M., Hausknecht, S., & Zhao, Y. (2016). Developing Learning Analytics Design Knowledge in the "Middle Space": The Student Tuning Model and Align Design Framework for Learning Analytics Use. *Online Learning*, *20*(2). doi: 10.24059/olj.v20i2.783

Zhang, Z. H., & Linn, M. C. (2011). Can generating representations enhance learning with dynamic visualizations? *Journal of Research in Science Teaching*, *48*(10), 1177–1198. doi: 10.1002/tea.20443

APPENDIX A

ENERGY-MATTER SUBCATEGORY RUBRIC

Table 1: Rubric for the subcategories of the Energy-Matter KI rubric used in Study 2. These subcategories correspond to the key events depicted in the Mechanistic Photosynthesis Animation. The E-M score criteria function as a key for assigning the type of link (energy, matter, or both) for a score of 4 or 5 in the subcategories.

Overall KI Score	***Sample Student Responses***			
1 - Assigned if response is off-task	Example: "Stuff."			
2 - Assigned if response is on-task, but non-normative OR does not specifically mention energy/matter transformation	Example: "It shows that plants have an effective method of producing glucose and water."			
Event Categories				
	Inputs and Outputs	***Water Splitting***	***Hydrogen Energy Transfer***	***Glucose Synthesis***
3 - Partial Energy or Matter Link Assigned if response receives no higher than 3 on any rubric category	Example: "Photosynthesis shows the process of of light energy turning into glucose and water."	Example: "It shows how the energy breaks apart the water molecule into hydrogen atoms and oxygen gases. Then the hydrogen atoms and the carbon dioxide combine to form water and glucose."	Example: "The water molecules get hit by photons. The atoms break apart and the hydrogen atoms power up the energy in a energy carrier. Then the hydrogen goes to the carbon dioxide, and if there are enough, then the glucose machine gets activated. In the other hand the oxygen gets released."	Example: "It shows how the energy breaks apart the water molecule into hydrogen atoms and oxygen gases. Then the hydrogen atoms and the carbon dioxide combine to form water and glucose."
4 - One Energy or Matter Link **Assigned if response receives only one 4 out of all rubric categories OR receives a 5 on the glucose synthesis category, but not higher than a 3 on all other categories**	Example: "When water and light energy (photons) enter the chloroplasts, the light energy breaks up the water into hydrogen and oxygen and the hydrogen gives the energy to make glucose."	Example: "It shows the Law Of Conservation Of Matter because none of the atoms were destroyed, or created, they were just rearranged. Also, the light energy is powering the chlorophyll, which is taking the water molecules apart, and rearranging them into O2, and the plant is saving up the hydrogen atoms. Also, the movement of the hydrogen molecules is filling up the battery molecules to create Glucose."	Example: "The light energy from the photons travels into the chlorophylls and vibrates them, and the vibrations split the water molecules into oxygen and hydrogen. The energy is transferred to the hydrogen and used to make the energy wheel spin. Then energy from the spinning wheel charges the energy carrier, and is stored in the glucose maker until the required amount of full energy carriers is present. Then the energy is used to make a glucose molecule."	Example: "It shows the process of water becoming energy, that then helps the "glucose machine" to make glucose. Since the plant needs energy to let cells move around and make glucose."
5 - Multiple Energy and/or Matter Links **Assigned if response receives more than one 4 OR assigned a 5 on the glucose synthesis category and a 4 in one other category**	This score is not applicable for this event category.	Example: "The light energy from the photons travels into the chlorophylls and vibrates them, and the vibrations split the water molecules into oxygen and hydrogen. The energy is transferred to the hydrogen and used to make the energy wheel spin. Then energy from the spinning wheel charges the energy carrier, and is stored in the glucose maker until the required amount of full energy carriers is present. Then the energy is used to make a glucose molecule."	This score is not applicable for this event category.	Example: "When light hits water molecules, the water molecules separate and hydrogen atoms travels toward the wheel and the energy moves the wheel and charges the battery. Now that the battery is charged it gets stored in the glucose machine and it happens over and over again until it's energy carriers are charged up with energy. Carbon Dioxide and Hydrogen go into glucose machine and take the energy to form glucose."

Energy-Matter Score Criteria

Type of Link*	**Corresponding Category Scores**
EM	5-Water Splitting
M	4-Water Splitting
M	4 or 5-Glucose Synthesis
M	4-Inputs and Outputs (discusses matter transformation)
E	4-Inputs and Outputs (discusses energy transformation)
E	4-Hydrogen Energy Transfer

Note: EM can also be achieved by meeting the criteria for an E and an M)

* (E=energy, M=matter, EM=energy AND matter)

APPENDIX B

PHOTOSYNTHESIS UNIT COMPARISON TABLES

The tables below list the steps (including their title, item types, and item prompts) composing the two photosynthesis units used in this dissertation project. The diagrammed researcher-designed unit used in Study 2 is listed first, corresponding to the first three table sections. The next three table sections are of the co-designed unit created in Study 3 and used in Studies 4 and 5. The step titles in the tables below have been color-coded to indicate which items in the units were either identical or substantively similar. Matching colors indicate similar steps. Lessons with no similar steps were collapsed and listed with the lesson number, title, and total step count.

Researcher-designed Photosynthesis Unit (Used in Study 2)		
Step Titles	Item Type	Prompt
1.1: Raw Ingredients to Make Food	Interactive Animation	
	MultipleChoice	What do you think happens to the light energy after it hits a leaf?
	OpenResponse	Deborah thinks that plants store energy from light, but she knows that plants don't have light inside them - plants don't glow in the dark! How do you think plants store energy from light?
1.2: Plants Can't Store Light	MultipleChoice	Plants cannot store light! But, plants can use light energy to make glucose (a kind of sugar). To make the sugar (glucose), the plant needs to put together several molecules. Using light energy to make glucose is called Photosynthesis means light and synthesis means putting together. The plant uses light energy to put something together, and when it is done it has:
1.3: Chlorophyll Captures Light Energy	MultipleChoice	To use light energy, first the plant has to capture it. Leaves are the best part of the plant for that. Cells in the leaves have special molecules that can catch light energy and transform it. The molecule that catches the light energy is called chlorophyll. Each cell in a plant's leaves has many stacks of chlolophyll in a pouch called the chloroplast. The picture shows a chloroplast with stacks of chlorophyll. Where in the plant cell does photosynthesis happen?
1.4: What Do Plants Need to Make Sugar?	Interactive Quiz	
2.1: Glucose plus...?	MultipleChoice	How many TOTAL atoms of carbon does the plant have?
	MultipleChoice	How many TOTAL atoms of hydrogen does the plant have (remember, each water molecule has 2)
	MultipleChoice	How many TOTAL atoms of oxygen does the plant have (remember, both carbon dioxide and water have oxygen)
	MultipleChoice	Look at the totals for each atom and the recipe for glucose. What does the plant have EXTRA of?
	OpenResponse	Think about the kind of atom that the plant has extra of. What do you think happens to it?
2.2: How is Energy Transformed? Initial Ideas	Informative Image+Animation (Video)	
	OpenResponse	Photosynthesis transforms light energy (from photons) into chemical energy (stored in glucose). What does this video show about the flow of energy through the photosynthesis process?
2.3 A: How is Energy Transformed? Let's Break This Down.	Informative Image+Animation (Video Clips)	
	MultipleChoice	Watch the photon in the clip below. The photon (light energy) hits the chlorophyll, transferring energy that makes the chlorophyll vibrate. The vibrations are so strong they break the water molecule into atoms. Photons are light energy. In the video, the photon disappeared. What happened to the energy?
	MultipleChoice	Watch the hydrogens in the clip below. The hydrogens are moving fast. They have a lot of movement energy. When the hydrogens hit the energy wheel, they transfer their energy to the energy wheel, making the wheel turn. Where did the energy wheel get the energy to turn?
	MultipleChoice	Watch the energy wheel in the clip below. The movement energy in the wheel is transformed into chemical energy to charge up the energy carrier molecule from low energy to high energy. After charging the energy carrier, the wheel has less energy and can't move. What happens to the movement energy from the energy wheel?
	MultipleChoice	Watch the molecules in the clip below. When all the needed molecules are there, they enter the glucose machine and are rearranged into glucose and water. This process transfers the energy from the energy carrier molecules to the new glucose molecule and the 6 water molecules. Glucose stores chemical energy. After glucose is made, why are the energy carrier molecules low energy instead of high energy molecules?

Researcher-designed Photosynthesis unit, Part 1

2.3 B: How is Energy Transformed? Let's Break This Down.	Informative Image+Animation (Video Clips)	
	OpenResponse	Watch the photon in this clip. Photons are light energy. In the video, the photon disappeared. What happened to the energy?
	OpenResponse	Watch the hydrogens in this clip. Where did the energy wheel get the energy to turn?
	OpenResponse	Watch the energy wheel in this clip. What happens to the movement energy from the energy wheel?
	OpenResponse	Watch the molecules in this clip. After glucose is made, why are the energy carrier molecules low energy instead of high energy molecules?
2.4: How is Energy Transformed: Reflection	Informative Image+Animation (Video)	
	OpenResponse	Now that you've thought about it more, revise your answer: Photosynthesis transforms light energy (from photons) into chemical energy (stored in glucose). What does this video show about the flow of energy through the photosynthesis process?
2.5: Chloroplast MC	Informative Text+Image	
	MultipleChoice	What is the main function of chloroplasts in a plant cell?
2.6: Chloroplast Explain BRANCH	OpenResponse	Now, explain in detail HOW do chloroplasts perform the main function in a plant cell that you selected in the previous step.
2.7 A: Mary's Chloroplast Explanation	Labeling	Another 7th gr. student, Mary, wrote an explanation for what is the chloroplast's main function in a plant cell. The computer told Mary: Go back to Step 2.2 to see, HOW does the plant use light energy to make food? Then, add to your explanation. Mary needs your help. Click on the RED part of the label. Then, a text box will appear. Edit the label in the text box. Describe to Mary an idea to add. Place the black dot where you think she should ADD this idea. (Hint: Go to Step 2.2 if you want information on how the plant uses light energy to make food.)
2.8 A: Revise YOUR Chloroplast Explanation	OpenResponse	Now it's YOUR turn to get feedback and revise your explanation: Explain in detail HOW chloroplasts perform the main function that you selected before. Your explanation is below. When you are done writing, press submit and the computer will give you feedback. Use this feedback to improve your story.
2.9 A: Mary's Revised Explanation	Labeling	Mary used your feedback to ADD an idea to her explanation for: What is the main function of chloroplasts inside of a plant cell? Take a look - How'd she do? Add a new label to give Mary a final comment on how well she revised. To add a label, click "New Label" and then click where you want the label to go.
3.1: GreenRoof Energy Story	OpenResponse	You have learned how light energy is transformed. Now, with your partner discuss: Mary heard that if plants are growing on a roof, the building won't need to use as much air conditioning (AC). But, Mary does not understand why and how plants would help. Write an Energy Story to explain to Mary what happens to energy from the sun in the picture. How could growing plants on the roof reduce the need for AC (and save energy)?
3.2 A: Mary's GreenRoof Energy Story	Labeling	Mary wrote an energy story to explain how growing plants on a roof could reduce the house's energy usage? The computer told Mary: Explain HOW the energy changes in the chloroplast. Then, revise your story. Mary needs your help. Click on the RED part of the label. Then, a text box will appear. Edit the label in the text box. Describe to Mary an idea to add. Place the black dot where you think she should ADD this idea.
3.3 A: Revise YOUR GreenRoof Energy Story	OpenResponse	Now it's YOUR turn to get feedback and revise your Energy Story: Mary heard that growing plants on a roof could reduce the house's energy usage. But, Mary does not understand why and how plants would help. Explain to Mary what happens to energy from the sun in the picture. How could growing plants on the roof lower the house's energy usage? Your story is below. When you are done writing, press submit and the computer will give you feedback. Use this feedback to improve your story.

Researcher-designed Photosynthesis unit, Part 2

3.4 A: Mary's Revised Energy Story	Labeling	Mary used your feedback to REVISE an incorrect idea in her energy story to explain how growing plants on a roof helps a house reduce its energy usage. Take a look - How'd she do? Add a new label to give Mary a final comment on how well she revised.
3.5: Where Does Cellular Respiration Take Place?	Interactive Animation	
	MultipleChoice	Where does cellular respiration happen?
3.6: Cellular Respiration in Mitochondria	Interactive Animation	
	MultipleChoice	Mitochondria take glucose molecules and release the stored chemical energy from glucose. Where do glucose molecules come from?
3.7: What Is Happening in the Mitochondria?	Interactive Animation	
3.8: How Is Energy Released?	Interactive Animation	
	OpenResponse	Answer Question 1. Explain what happened to glucose.
	OpenResponse	Answer Question 2. What was released from the glucose?
	OpenResponse	Answer Question 3. Explain what happened to hydrogen and oxygen.
3.9: Opposite Systems	MultipleChoice	Glucose and oxygen gas are....
	MultipleChoice	Carbon dioxide and water are...
	MultipleChoice	What is the one ingredient that the plant needs for photosynthesis that is NOT released during cell respiration?
	MultipleChoice	If a plant is in a clear box and has light and water, but only has the air in the box, will the plant grow?
	OpenResponse	Explain your choice. Use evidence from your understanding of photosynthesis and cell respiration.
3.10: Cellular Respiration and Photosynthesis	Interactive Quiz	
3.11: What happens at night?	Image	
	MultipleChoice	Do you think a plant can stay alive without light?
	OpenResponse	Explain your reasoning.
Lesson 4 - Plant Growth & Graphing (11 steps)		
5.1: Animals need plants	Informative Text+Image	
	MultipleChoice	The organelle that allows plant cells to produce their own glucose is:
5.2: Humans need energy	Informative Text+Image	
	OpenResponse	What would happen if we didn't have mitochondria?
5.3: Sunlight Energy Story	OpenResponse	How does energy from the sun help animals to survive? When you are done writing, press submit and the computer will give you feedback. Use this feedback to improve your story.
5.4: Great Job	Image	
Lesson 6 - Extra for Experts (2 steps)		

Researcher-designed Photosynthesis unit, Part 3

Table 0: Diagram of the researcher-designed photosynthesis unit used in Study 2.

Co-designed Photosynthesis Unit (Created in Study 3, Used in Studies 4 and 5)		
Step Titles	Item Type	Prompt
1.1: Anchoring Phenomenon: Biosphere 2	Informative Video	
	OpenResponse	What would plants and animals need to survive in a closed space like Biosphere 2?
1.2: Eliciting Ideas: The Sun and Plants	Informative Text+Image	
	OpenResponse	What do you think is the relationship between solar energy and plant growth?
1.3: Adding & Distinguishing Ideas: Energy & Plant Growth	Informative Text+Image	
	Match	Use the image above to help you place these statements in the correct space.
	OpenResponse	Based on these images, describe the relationship between solar energy and plant growth?
	OpenResponse	What do you think is the cause of this relationship between solar energy and plant growth?
1.4: Eliciting Ideas: Carbon Dioxide	Informative Text+Image	
	OpenResponse	What do you think is the relationship between the time of year and the amount of carbon dioxide in the atmosphere.
1.5: Adding & Distinguishing Ideas: CO2 Levels in the Atmosphere	Informative Text+Image	
	Informative Text+Image+Video	
	MultipleChoice	I agree with
	OpenResponse	Use evidence from the animation and what you know to explain your choice. (Be sure to discuss by HOW and WHY the levels of CO2 to change.)
1.6: Eliciting Ideas: Plant Growth	Informative Text+Image	
	OpenResponse	In addition to solar energy, what else do you think plants need to grow?
1.7: Adding & Distinguishing Ideas: Understanding What Plants Need	Informative Text+Image	
	Match	Use the images above to help you place these statements in the correct space.
1.8: Distinguishing Ideas: What Plants Need	Informative Text+Image+Video	
	OpenResponse	Based on all the data that you have seen so far, what do you think is the relationship between: time of year, solar energy, carbon dioxide, rainfall, and plant growth?
1.9: Eliciting Ideas: Photosynthesis	Informative Text+Image+Video	
	OpenResponse	How do you think plants use light, carbon dioxide, and water to make glucose?
1.10: Adding Ideas: Chemical Reactions in the Plant	Informative Text+Image	
	Match	How many atoms of Carbon, Hydrogen, and Oxygen are there in one glucose molecule?
	MultipleChoice	The plant gets the carbon it needs to make glucose from which of the 3 things that helps it grow?
1.11: Adding & Distinguishing Ideas: Photosynthesis Animation	Informative Text+Image	
	Interactive Animation	
	OpenResponse	Based on the animation, what do plants use the sun's energy for?

Co-designed Photosynthesis unit, Part 1

1.12: Distinguishing Ideas: MyModel-Energy Transfer in Photosynthesis	ConceptMap	TASK: Create a model showing how energy is moved (transferred) and changed (transformed) during the photosynthesis reaction.
1.13: Distinguishing Ideas: Understanding the Photosynthesis Reaction	Informative Text+Image	
	MultipleChoice	Based on the animation, what is the main function of chloroplasts in a plant cell?
	OpenResponse	Explain in detail HOW chloroplasts perform the main function you just selected.
	Match	Which atoms are used to make glucose and oxygen gas?
	OpenResponse	Use evidence from the photosynthesis animation to support the statement that energy and matter cannot be created or destroyed, only changed. (Be sure to talk about energy AND matter.)
1.14: Connecting Ideas: Energy and Matter Transformations in Photosynthesis	Informative Text+Image	
	MultipleChoice	Which of the following is matter? (You may select more than one answer.)
	OpenResponse	Explain how MATTER moves and changes during photosynthesis. Be sure to include new ideas and each item from the animation (look at the picture above).
	OpenResponse	Explain how ENERGY moves and changes during photosynthesis. Be sure to include new ideas and each item from the animation (look at the picture above).
1.15: Anchoring Phenomenon: Biosphere 2	Informative Image	
	OpenResponse	Use what you have learned to improve your response. What would plants and animals need to survive in a closed space like Biosphere 2?
2.1: Eliciting Ideas: Why Do Animals Eat?	Informative Image	
	OpenResponse	Why do animals (including humans) need to eat food?
2.2: Adding & Distinguishing Ideas: Why Animals Eat (VIDEO)	Informative Video	
	MultipleChoice	Why do animals (including humans) need to eat?
2.3: Adding & Distinguishing Ideas: Energy and Matter	Informative Image	
	OpenResponse	The sun provides plants with ENERGY, but what provides plants with the MATTER they need to grow?
	OpenResponse	Why do animals need to eat food? Revise your previous response to discuss the role of energy and matter.
2.4: Connecting Ideas: MyModel-Plants and Animals	Table	
	ConceptMap	
2.5: Eliciting Ideas: Food Energy	Informative Text+Image	
	OpenResponse	How do you think your body gets all this energy out of food?
2.6: Adding & Distinguishing Ideas: How To Get To Glucose?	Informative Text+Image	
	MultipleChoice	What part of the body breaks down food pieces to glucose or glucose pieces?
2.7: Eliciting Ideas: Energy In Glucose	Informative Text+Image	
	OpenResponse	How do you think plant and animal cells get the energy out of glucose? (Hint: Think about how the energy got into the glucose.)
2.8: Adding & Distinguishing Ideas: Plants and Animals	Informative Text+Image	
	OpenResponse	What do you notice about photosynthesis and cellular respiration? (Hint: How are they alike, how are they different?)
	Informative Text+Image	
	Interactive Quiz	

Co-designed Photosynthesis unit, Part 2

2.9: Adding & Distinguishing Ideas: Cell Respiration Animation	Informative Text+Image	
	Animation (Video)	
	OpenResponse	Answer Question 1. Explain what happened to glucose.
	OpenResponse	Answer Question 2. What was released from the glucose?
	OpenResponse	Answer Question 3. Explain what happened to hydrogen and oxygen atoms.
	Informative Text+Image	
	OpenResponse	Describe how energy carriers should be included to improve Paula's animation. (Hint: Explore the photosynthesis animation in Step 1.11 to see how the energy carriers helped make glucose, now reverse that step of the process.)
2.10: Connecting Ideas: Energy from the Sun (Energy Story)	Informative Text+Image	
	OpenResponse	Write an energy story below to explain your ideas about how animals get and use energy to survive. Be sure to explain how energy and matter move AND how energy and matter change.
2.11: Revising Ideas: Energy from the Sun (Energy Story)	Informative Text+Image	
	OpenResponse	Revise your energy story to explain your new ideas about how animals get and use energy to survive. Be sure to explain how energy and matter move AND how energy and matter change.
2.12: Anchoring Phenomenon: Biosphere 2	Informative Image	
	OpenResponse	Use what you have learned to improve your response. What would plants and animals need to survive in a closed space like Biosphere 2?
Lesson 3 - Decomposers (5 steps)		
Lesson 4 - Ecosystems (11 steps)		

Co-designed Photosynthesis unit, Part 3

Table 1: Diagram of the Co-designed photosynthesis unit created in Study 3 and used in Studies 4 and 5.