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ITERATIVELY REFINING A SCIENCE EXPLANATION TOOL THROUGH CLASSROOM IMPLEMENTATION AND STAKEHOLDER PARTNERSHIPS

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Science inquiry challenges students to synthesize various ideas about complex phenomena into coherent explanations. It also challenges teachers, who must guide their diverse students' developing understanding during student-paced investigations. We describe the Idea Manager, a suite of web-based, curriculum-integrated tools that (a) guides students' knowledge integration as they generate, distinguish, and reconcile their ideas; and (b) provides means for teachers to monitor learning over the course of technology-enhanced science inquiry units. With the Idea Manager tool, students document short, text-based ideas, tag and sort them along various attributes, and exchange them with classmates. At culminating points of their investigations, students graphically organize their ideas to prepare written scientific explanations. Meanwhile, logs of idea entries, revisions, and meta-data inform teachers' and researchers' decisions about instruction and design.

This paper offers an account of the design moves made in refining the Idea Manager, and highlights the importance of teacher-researcher partnerships and classroom implementations. Through designers' artifacts, classroom research findings, and teachers' and researchers' reflections, we illustrate the tool's origins; our strategies for testing new features and eliciting stakeholders' feedback, and how middle and high school classroom implementations inform the tool's continued iterations. Based on learning theory and on our own 40+ collective years of classroom teaching experience, we explain our design decisions and describe how new features and patterns for the tool's use emerged from a community of researchers. Finally, we reflect on the process of iteration that advances both theory and design, and on the value of pedagogically-driven technology design.

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INTRODUCTION

Students' written explanations are often used to assess their understanding of science topics, and their ability to engage in scientific discourse. Constructing explanations is also an important practice in authentic scientific investigations. However, by relying only upon students' final explanations, teachers and researchers can fail to see the complex processes that students undertake to formulate them, and therefore miss opportunities to recognize students' understanding, and to provide the necessary support along the way.

In this design case, we report on the Idea Manager (IM), a suite of tools integrated into a web-based curriculum platform, and intended to scaffold students' explanations. By also revealing intermediate points during the process of explanation construction, the IM produces a record of students' processes of explanation, which informs teachers in guiding their students' learning, and researchers in refining curriculum and tool design. We describe our process of designing the IM and our underlying design rationale, which we refined through our experiences implementing the tool, findings from research studies, and conversations with various users. We reflect on ways the tool has succeeded, ways that it can be improved, and on directions for its continued design.

BACKGROUND AND THEORETICAL FRAMEWORK

The Web-Based Inquiry Science Environment

The Web-based Inquiry Science Environment (WISE, http://wise.berkeley.edu) is a free, open source curriculum platform used by more than 12,000 teachers and over 100,000 students around the world. It offers research-based, classroom-tested units on science topics across the middle and high school standards. In addition, WISE provides authoring tools for creating new units and for customizing existing ones.

A typical classroom implementation of WISE involves student pairs (workgroups) collaborating on shared computers while their teacher circulates to offer guidance as needed. Students typically spend 5-10 days investigating a socio-scientific question. They explore simulations, design and conduct virtual experiments, interact with animated and interactive media, generate diagrams, graphs, and essays, and exchange ideas with their peers both online and face-to-face.

The Knowledge Integration Framework

The design of WISE units, assessments, and teacher professional development is guided by the Knowledge Integration (KI) framework (Linn & Eylon, 2011). This framework synthesizes research that shows that students begin science classes with disconnected, fragmented, and often inconsistent ideas about science; and describes how learning occurs when students integrate these ideas into a coherent understanding. The KI framework offers an instructional pattern that guides the principled design of inquiry-based instruction. KI instruction first elicits students' initial ideas to help anchor new knowledge to their prior experiences. Next, it adds new normative ideas by engaging students with scientific visualizations, virtual experiments, and hands-on activities. Following this, KI instruction scaffolds students' processes for organizing, distinguishing, and connecting these ideas. This instructional pattern emphasizes students' continual reflection on their ideas as they eventually construct and articulate an integrated understanding of a science topic.

Both teachers and researchers commonly rely on students' culminating written explanations as evidence of their conceptual science understanding. In our classroom observations and interactions with teachers and students, we found that these explanations did not capture the totality of what students actually understood, nor how their understanding might have evolved over time. Rather, informal conversations with students during their work, in which teachers and researchers could probe students' understanding and elicit ideas not expressed in their written work, tended to reveal nuances about their understanding that were not represented in students' final explanations. From these conversations, it was clear that many students had difficulty tracking their various ideas, and did not always get the needed support for documenting and organizing these ideas at the right time. In real time, teachers were hard-pressed to notice and recall which students needed help, and when.

We also noticed from our experiences in the classroom that students had many ideas worth building upon. Although some of students' ideas were less well developed than others, and not all were normative, we observed from collaborative classroom activities and class discussions ways that students could benefit from drawing upon one another's ideas as resources in learning. We thus designed the IM to make the process of building scientific explanations more explicit. Students use the IM to document ideas over the course of a unit, to share these ideas with their peers, and to refer to those ideas when later writing more elaborate, prompted explanations. This tool, we reasoned, would encourage students to continually reflect upon their thinking, to benefit from the ideas of others, and to allow teachers to monitor and guide students' developing understanding.

DESIGN MOTIVATION

Guided by the Knowledge Integration framework, the IM was designed to support three complementary sets of goals in the areas of learning, teaching, and research. Below, we elaborate on these goals and on how the tool's features support them.

A Scaffold to Support Student Learning

The IM's primary purpose is as an instructional scaffold for students to construct scientific explanations. Research on students' science learning, as well as our conversations with teachers and our prior experiences with classroom research, reveal the challenges students experience when constructing scientific explanations (Gerard et al., 2016). Explanation requires students (a) to distinguish and coordinate among many ideas, not all of which are consistent with one another (Kuhn et al., 1995; Schauble, 1996); (b) to support arguments with evidence and to revise them when new evidence emerges (Chinn & Brewer, 1998; Kuhn, 1989; Sandoval,2004); and (c) to articulate their explanations in writing (McNeill & Krajcik, 2008; Sandoval, 2004; Sandoval & Millwood, 2005). It is rare for students to engage in planning activities—such as generating, organizing, and linearizing ideas—that would support the complex process of explanation (Andriessen, Coirier, Roos, Passerault, & Bert-Erboul, 1996). Instead, students are often quick to draw conclusions from limited evidence before considering alternatives (Zeidler, 1997); they rely on information from single rather than from multiple sources (Oliver & Hannafin, 2000), and they fail to revise their arguments even in light of new evidence (Chinn & Brewer, 1998). Our intention was for the IM to break down the explanation process into a series of well-defined tasks, thus making each task more manageable, and also providing students with opportunities to pause, reflect on their process, and assess their understanding.

A Record of Students' Developing Understanding to Support Teachers in Giving Guidance

Students are most successful at building complex explanations when they receive continuous guidance and scaffolding (Quintana et al., 2004). However, a given classroom has many students, each with different levels of ability, and no single technology can address each student's unique needs; nor can a single teacher of large classes provide the timely, personalized support that would benefit each student.

A data logging system in WISE captures students' uses of the IM and displays this information for teachers to monitor. Through the grading interface, teachers can view the range of ideas students document and the ways they organize these ideas when prompted to construct explanations. Using this information, teachers can monitor students' developing understanding and decide on appropriate interventions, such as (a) stop for whole class discussion, (b) offer individual guidance face-to-face or through the grading interface, or (c) adapt future instruction by reinforcing previous activities with which students may have struggled and skipping upcoming activities that students may have sufficiently grasped. In this manner, the IM allows teachers to provide students with the continual support they need throughout the process of explanation, and which is not always feasible within the constraints of typical classroom environments.

A Tool for Research Into Students' Sensemaking and Collaboration

The data logged by the WISE system offers researchers the ability to study how students' use their scientific ideas to

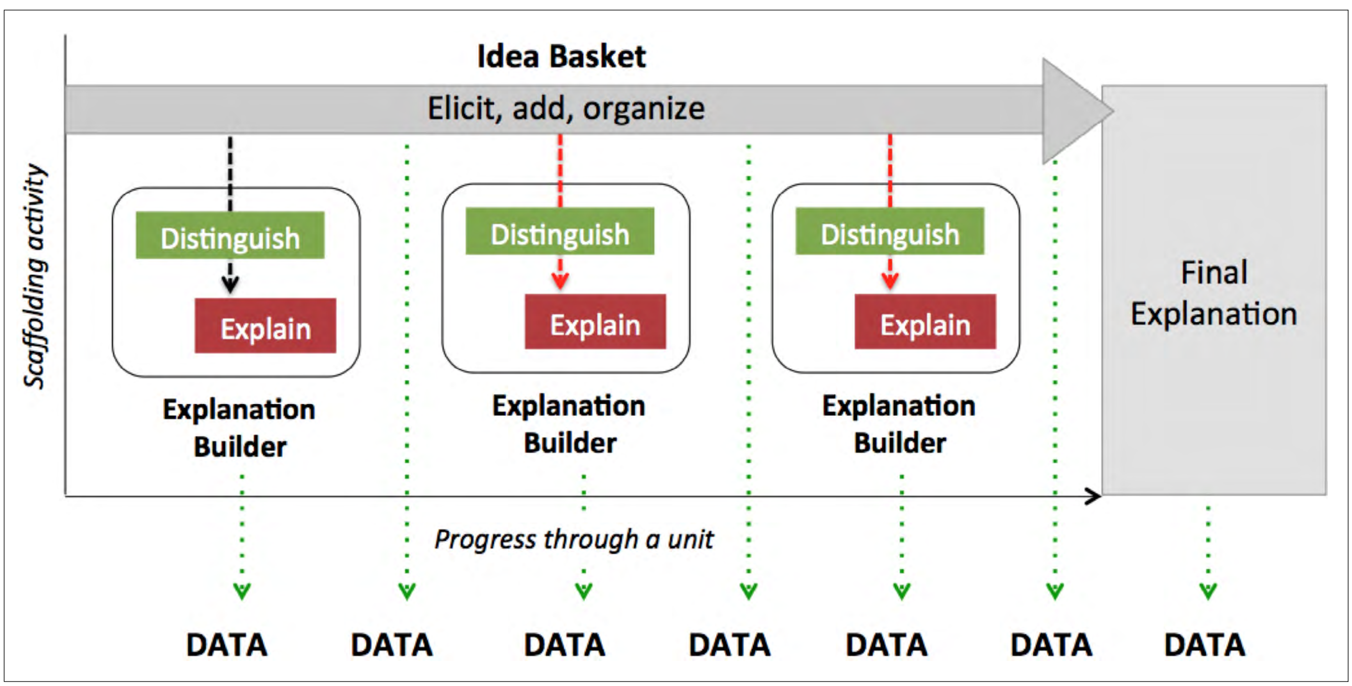

FIGURE 1. The Idea Manager makes explicit the process of Knowledge Integration.

support explanations (Matuk & King Chen, 2011; Matuk & Linn, 2013, 2014, 2015; McElhaney, Miller, Matuk, & Linn, 2012). Information on which steps in a unit students add their ideas, the contents of those ideas, which ideas are public, and when and who takes these ideas up into their own Idea Baskets, is powerful evidence of students' evolving understanding, and of the role of their peers' ideas in supporting that understanding. Researchers worked closely with developers to determine which information should be logged, and how it should appear in exported spreadsheets to facilitate analyses. That information makes possible a more detailed and nuanced account of student learning than is possible from typical embedded assessments (see Figure 1).

THE IDEA MANAGER FROM THE STUDENT'S PERSPECTIVE

Students encounter the IM early on in their progress through a unit. Depending on the unit's narrative, the IM might be framed as a tool for documenting observations, ideas, or information they wish to remember and to later revisit (see Figure 2A). At key points in the unit, students are prompted to add ideas about particular topics, occasionally guided by suggestions, and with a minimum number of ideas required to add before proceeding (e.g., "What do you know about cancer? Add two ideas before moving onto the next step."). Similar prompts may also invite students to re-evaluate, revise, or remove ideas entered previously. To help them later retrieve their ideas, students can assign tags and keywords to specify the source, relevance, and their own certainty of the ideas. Students are also able to share ideas with their classmates and to view their classmates' ideas within a public repository of ideas (see Figures 2B and 2C). At critical points in the unit, students arrive at an Explanation Builder step, in which they are prompted to distinguish and organize ideas by dragging them from their idea baskets and arranging them within author-generated categories (see Figure 2D). Students are then prompted to write a narrative explanation based on their organized ideas (see Figure 2E). This pattern of adding, revising, organizing, and writing may recur any number of times throughout students' work in a unit, depending on the unit's goals.

DESIGN PROCESS

The Core Design Team

The IM's design was accomplished by a team of researchers with diverse experiences in education, research, and technology design. Linn has led generations of research and design teams in the development and implementation of previous versions of WISE. Findings from her National Science Foundation (NSF) funded research have informed refinements to WISE and to the Knowledge Integration framework (Linn & Eylon, 2011).

Matuk was a postdoc advised by Linn at the time our team first began designing the tool, with a professional background in biomedical illustration, design, and animation. She was interested in making WISE units more collaborative, and to add features that tracked the knowledge integration process. McElhaney was a first-year postdoc with a professional background in materials science and engineering. His dissertation, supervised by Linn, investigated students' experimentation using a virtual experiment in a WISE physical science unit. King Chen was a doctoral student with a background in astrophysics, and experience as a curriculum designer of after-school science programs at the Lawrence Hall of Science. Lim-Breitbart has a Masters degree in Information Management and Systems, and had contributed to improvements and new features of WISE over his 10 years as a member of the WISE developers' team. Kirkpatrick is a retired middle school science teacher, who advised on early versions of WISE curriculum used on his classroom. He had since become a liaison among teachers, researchers, and developers, and used his insights into classroom teaching to advise on the design of the IM.

Teacher Involvement

Practicing teachers also contributed to the IM's design. Several teachers implemented units with the first release of the IM in their classrooms, and participated in interviews with researchers about their experiences. They, as well as approximately 20 other teachers who already taught using WISE, attended yearly summer workshops held at UC Berkeley. At a workshop early in the IM's design, we facilitated a design activity in which teachers created an initial design mockup for the tool. This activity helped us identify key design features for the IM and what student data teachers would need from it in order to be informed on their students' progress. In subsequent years, we held numerous discussions, in which teachers reviewed students' IM work and provided critical feedback on how the tool served their goals, and how it could be improved.

Establishing a Need

Our first team meetings had the goal of defining and articulating a set of specific needs for a new tool within WISE. For this, we drew on our collective experiences in classrooms as researchers, school teachers, and learners. We reflected on our individual approaches to documenting and integrating ideas during extended projects, such as authoring curriculum, writing dissertations and research articles, building furniture, and so forth. We also described the features we liked and disliked in tools that we used to organize our ideas, including corkboards and sticky notes, and online tools such as Evernote, Google Drive, and Pinterest. Additionally, we considered the successes and shortcomings of existing WISE tools, and on three such tools in particular: Sensemaker, the Brainstorm Discussion tool, and the WISE journal.

FIGURES 2A-E. The IM from the student's perspective in the context of a grade 7 unit on mitosis and cell division.

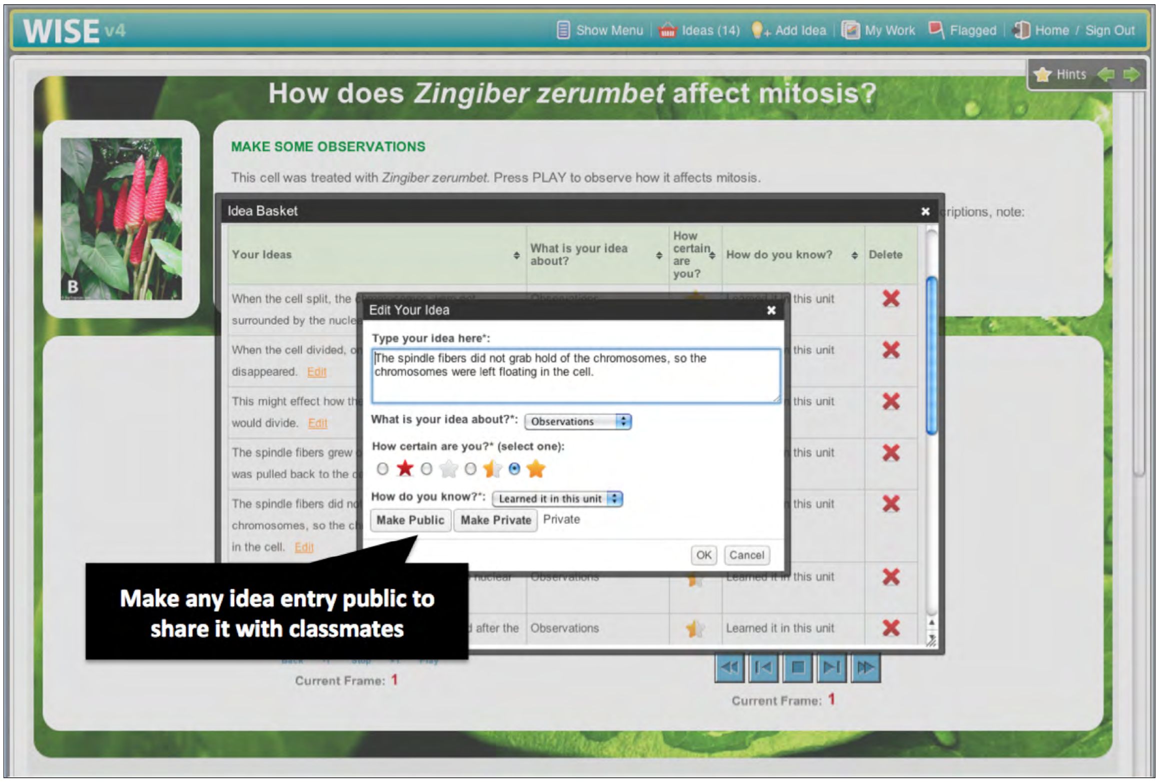

FIGURE 2A. The interface for adding ideas.

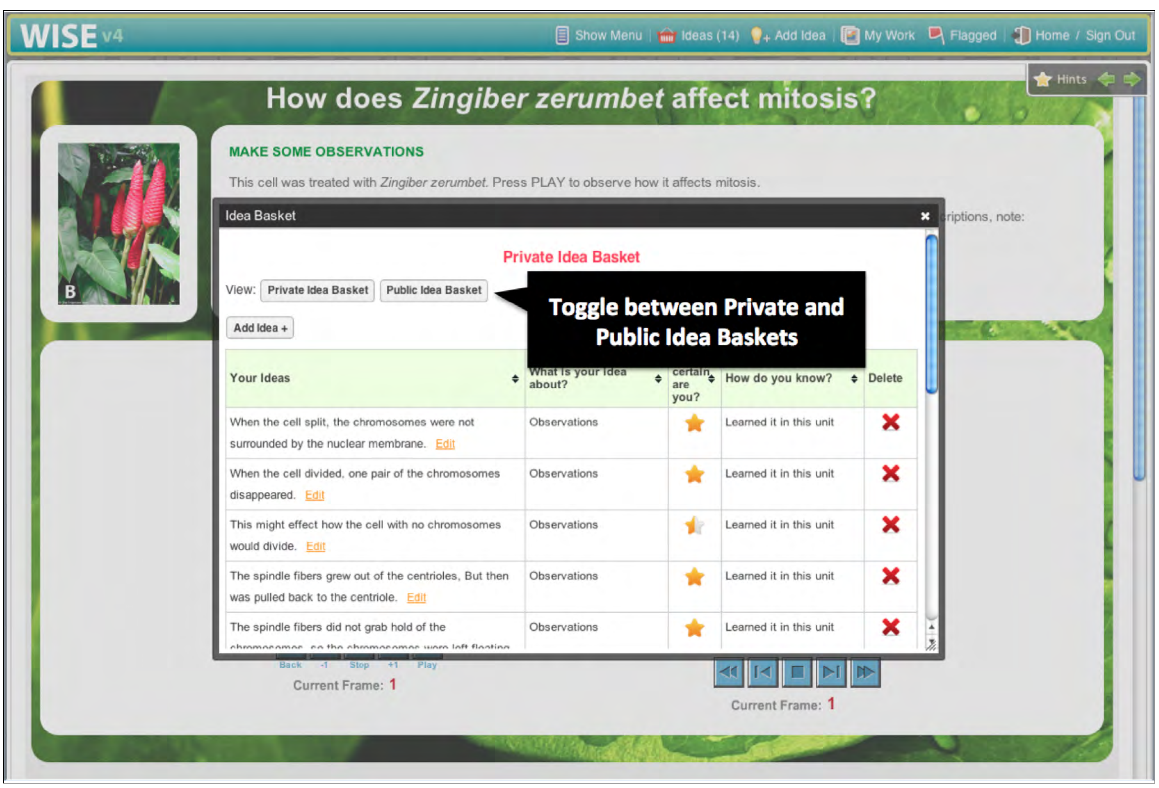

FIGURE 2B. The list of ideas generated by a single student workgroup, as seen in their Private Idea Basket.

FIGURES 2A-E (CONTINUED)

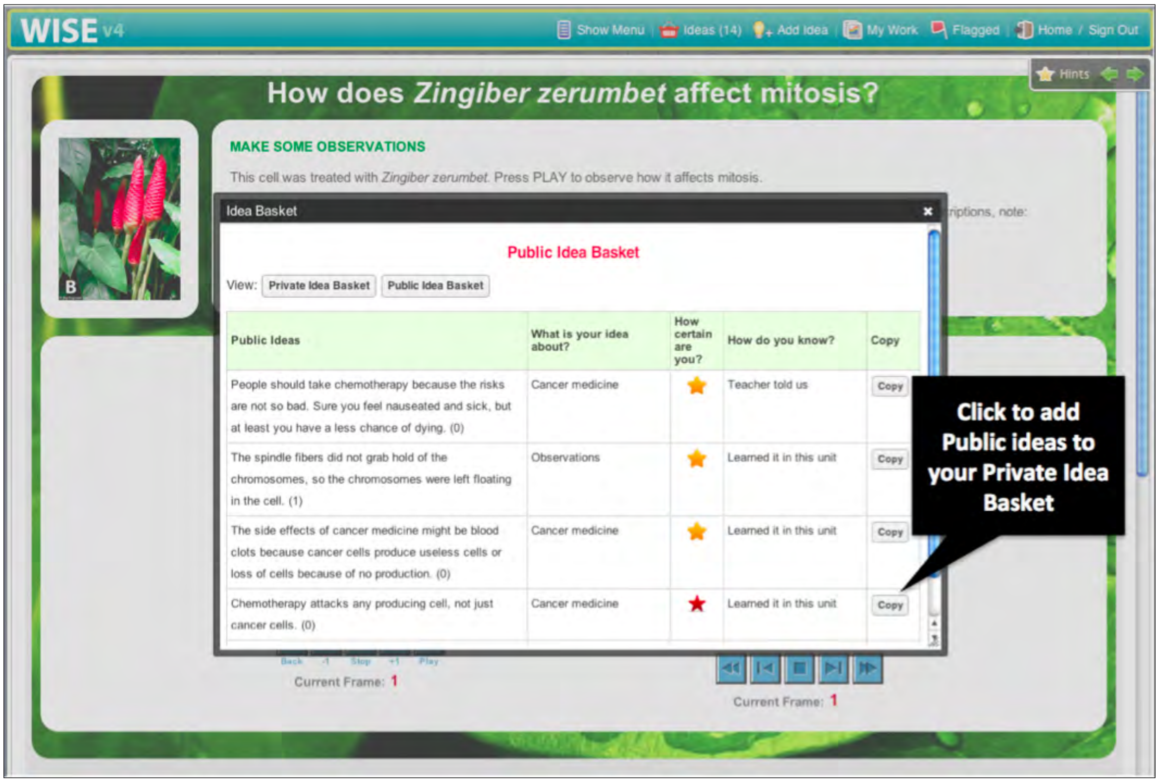

FIGURE 2C. The view of the Public Idea Basket.

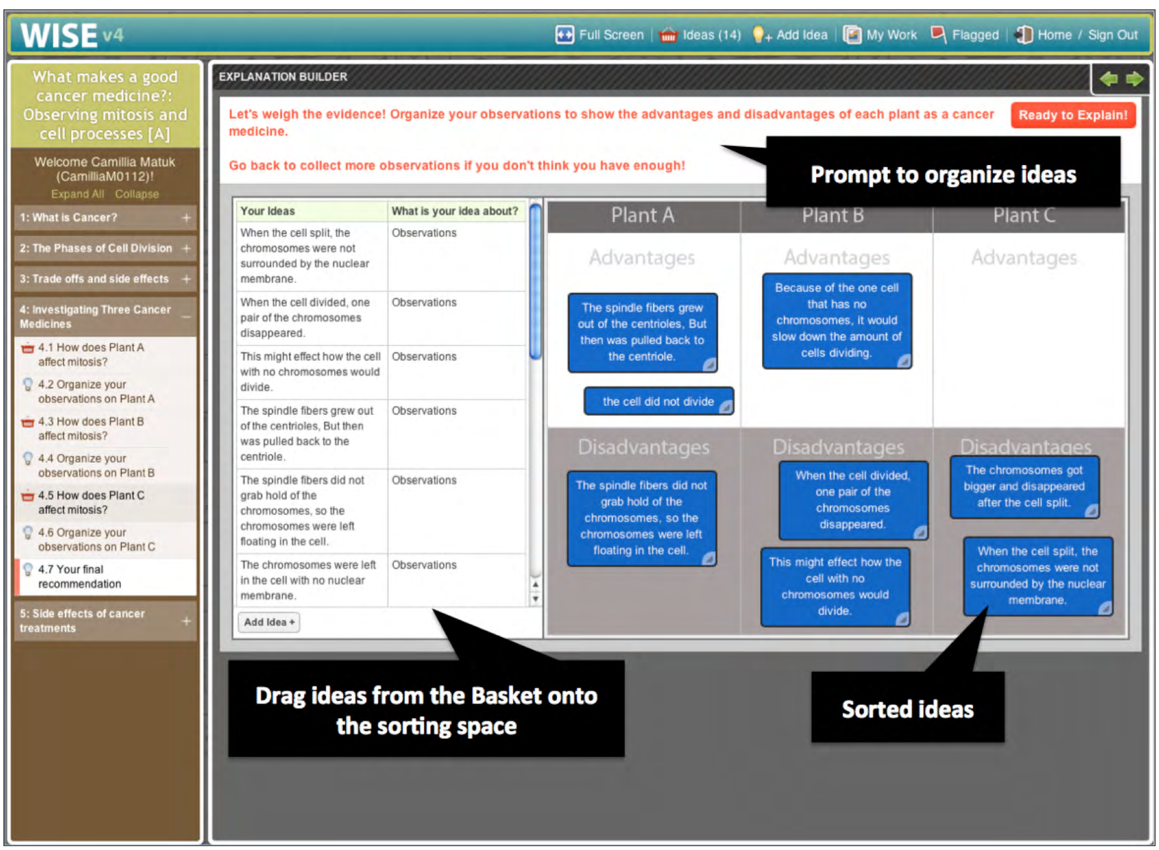

FIGURE 2D. The Explanation Builder, in which students sort their collected ideas into categories.

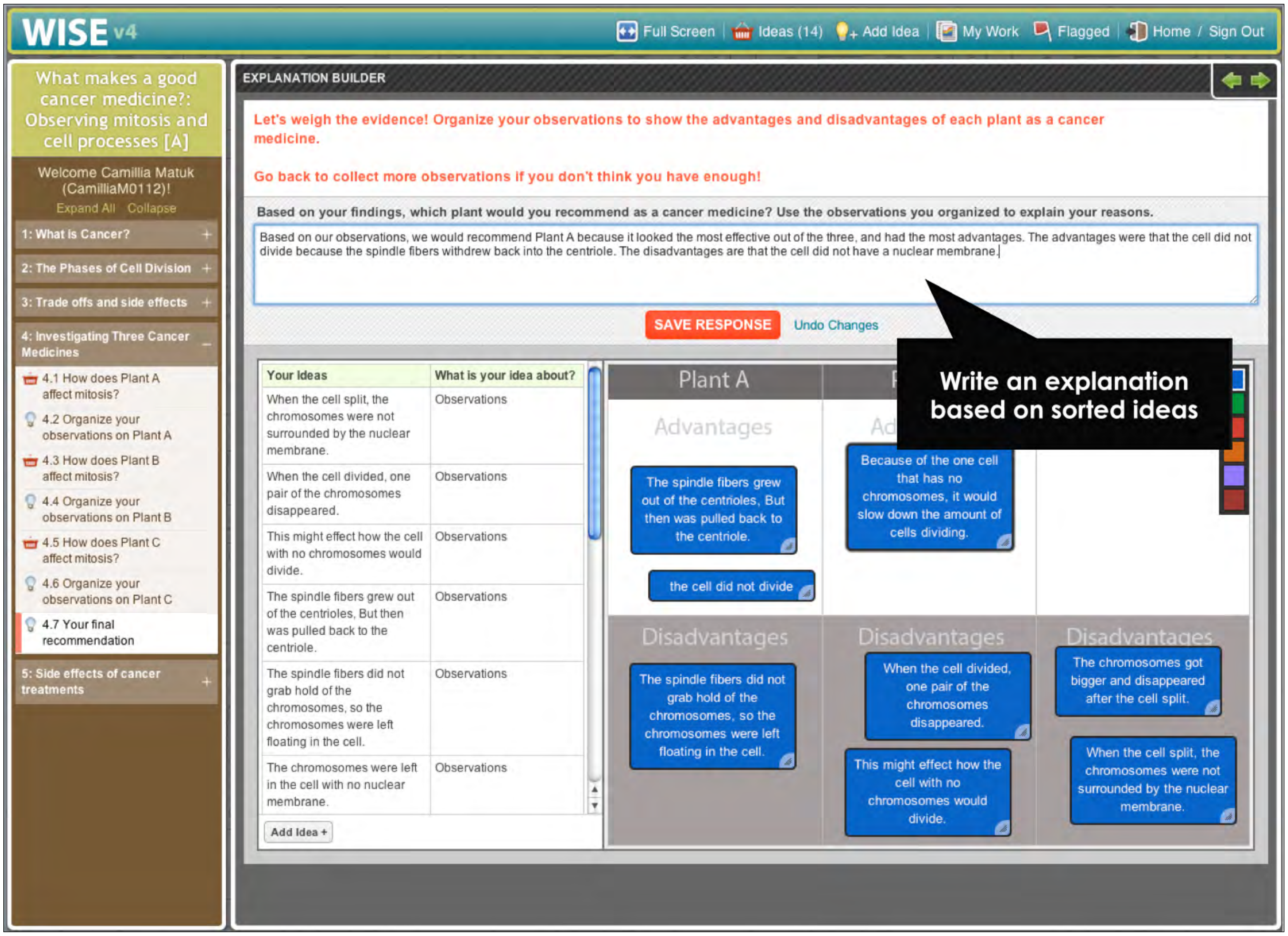

FIGURE 2E. The text field within the Explanation Builder, in which students generate written explanations based on their sorted ideas.

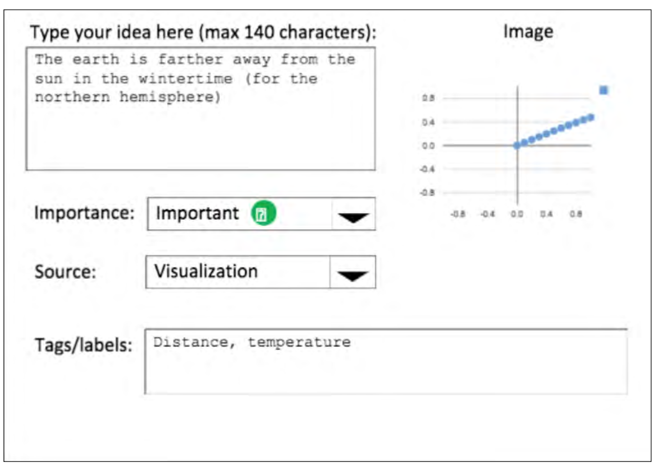

FIGURE 3. A mockup of the Idea Basket, created in Microsoft PowerPoint.

Sensemaker existed in prior versions of WISE to help students organize the components of evidence-based arguments (Bell, 1997, 2004; Bell & Linn, 2000; Linn, Clark, & Slotta, 2003). Although Sensemaker was highly successful for helping students organize ideas, it had a limited graphical interface, and lacked features that would allow students to integrate evidence collected from previous parts of a unit. Although it has since evolved, the Brainstorm Discussion at the time offered a flat, text-based discussion forum among classmates (e.g., Slotta & Linn, 2009), which enabled a rudimentary form of collaboration, but lacked scaffolds for structuring and organizing students' contributions around topics or principles, that would have helped organize more complex discussions. The WISE Journal was a text-based notepad that students could access at any time during the course of a unit to document their ideas. However, the tool lacked a way to help students manage, organize, or share these ideas. Ultimately, the Idea Manager merged and integrated promising design features from these three prior technologies.

Following our initial brainstorms, one member of our team reviewed and synthesized our meeting notes, and used PowerPoint to create a mockup of the student interface, which illustrated how the features our group had discussed might function within a couple of use cases (see Figure 3). Over email, the core team discussed and refined the mockup, which became the blueprint for the version of the IM we used in our first classroom pilot tests.

An Agile Approach to Refinement

We approached our design in a way that would allow us to make informed, systematic refinements. This was because, in spite of our many intuitions about what would make good features, we also had many questions. We were inspired by many of the commercial tools and personal strategies that were part of our personal workflows. However, we were careful to remember that the context of school and the motivations of middle and high school students were in contrast with our own: Features that were useful to us were not necessarily appropriate for scaffolding student learning in the classroom. Meanwhile, our perspectives on learning and instruction motivated general features of the tool, but the need to concretize these perspectives into a functional design raised questions about how we would do so. We knew, for example, that we wanted to encourage students to add ideas of their own throughout an investigation. But how should we frame this task? How often should we prompt it? What kinds of ideas students would add, and how should we scaffold the process of adding ideas? We also knew that we wanted students to organize their ideas in preparation for writing an explanation. But what categories and spatial arrangements would be most conducive to students for distinguishing and integrating their ideas?

Thus, rather than take the time at this initial stage to add the full range of features we thought the IM should have, we took an Agile approach to development (da Silva, Martin, Maurer, & Silveira, 2011). That is, we first built a basic working version—one that simply allowed students to document and organize their own ideas—that could be immediately tested in the classroom, and that would inform subsequent versions of the tool. Whenever there arose the option for the tool to support students in one way or another (e.g., should students use tags or keywords to organize their ideas?), we offered the choice to the author, and considered it an opportunity to observe what authoring practices would emerge, as well as what research studies might be conducted to better understand the impacts of such design choices on students' learning. Table 1 organizes the IM's key features within the Knowledge Integration framework, and details design revisions based on findings from classroom implementations.

How Design Solutions Emerged From Community-Based Iteration

With the first release of the IM, we began a series of classroom-based research investigations into the tool's affordances for learning, instruction, and research (see Table 2). Our core team began to incorporate the tool into selected units for classroom-based research studies. These units included a previously tested high school chemistry unit on recycling and a new unit on detergents (both led by McElhaney), a frequently used existing middle school life science unit on mitosis (led by Matuk), and a new high school earth sciences unit on the seasons (led by King Chen).

These first implementations were exploratory, and served as much to explore how the IM could help us support and understand student learning as they served to explore ways to improve the IM's design. Toward these ends, our research and design plans emerged from a cyclical process of expert review (Linn et al., 2003), through which we discussed our ideas, research plans, and classroom findings among members of our larger group. Members included postdocs, graduate students, and preservice teachers, who were also WISE users, and who had collective experience in research, classroom teaching, curriculum design, and science content. During regular meetings, we reflected upon and across units, and sought to identify the questions we could answer with the data that resulted, the questions that remained unanswered, and the further questions that our findings raised. New features thus emerged from a process of implementation, reflection, and discussion among this larger community of researcher-designers.

As was typical within this group, several members, including members of our core design team, took ownership over particular units. These units were the focus of classroom-based research programs around such topics as teacher guidance, student collaboration, peer feedback, and experimentation. Researchers' motivations for incorporating the Idea Manager into their units ranged from wanting to use it to investigate central questions about student learning, to simply having it support other main activities within a unit. As researchers designed for their individual goals, they also shared and offered reflections upon their work. When one member implemented an apparently successful integration of the IM, this became a model for other members integrating the IM into different units.

As we accumulated experiences with using the IM in classrooms, we also accumulated ideas for new features. New features tended to be proposed by individual authors for use within specific units, and were mostly based on insights from their recent classroom implementations. For instance, King Chen noticed that in an Explanation Builder step, students positioned ideas over the line between two categories to indicate that the idea belonged in both. She therefore proposed that the tool enable students to organize more than one instance of an idea within the same Explanation Builder space. In another example, McElhaney noticed that students' Idea Baskets quickly filled with ideas, and that it was burdensome for students to sift through ideas that were either no longer relevant, or not relevant to a particular task. He therefore proposed the ability for authors to specify whether and when students would have access to particular ideas. That is, authors could specify within a given Explanation Builder step that students should only be able to use a subset of their ideas, such as the ideas that were added on a specific earlier step. This feature would help authors streamline the amount of information students would encounter, and ensures that students would only see the information most likely to be

TABLE 1. The rationale behind the Idea Manager's main design features.

FEATURE	RATIONALE	FINDINGS FROM IMPLEMENTATION	DESIGN SOLUTION
Adding and Eliciting Ideas			
150 character limit on idea entries.	Encourages students to summarize key points in their own words, and discourages copying large amounts of text from the unit.	Some students found that the character limit constrained them in articulating their ideas. They circumvented this by writing single thoughts across a series of idea entries. This complicated certain research analyses.	Instruct students within the unit on the appropriate scope or type of ideas. Offer students examples of idea entries to use as models for their own.
Select the idea's source from a drop-down menu. Options include: evidence step, visualization, everyday observation, school/teacher, other (specify).	Allows students to keep track of the sources of their ideas.	Students ignored the field and left the default option selected, which made it an untrustworthy information source for research.	Students are required to choose one of the options from a drop-down list before they can fully submit their idea entry. This feature is optional and can be removed when not critical to the unit's goals.
A floating dialog box appears when students click the button to Add Ideas.	Allows students to add ideas without having to navigate away from the relevant step.	The dialog box sometimes obscured critical information to which students needed to refer when adding their ideas.	Instead of a floating dialog box, adding ideas might occur through an expandable side panel that does not obscure the content on the rest of the page.
Organizing Ideas			
Students can apply tags to their idea entries. Choices of tags are authorable and include "Other," which students can specify (limited to 15-characters).	Helps students to organize ideas within meaningful categories.	Tags varied in their usefulness across different units. It was not always clear whether and how students used them to make decisions about their own and their peers' ideas.	Attributes of ideas are customizable by the unit author to enable better alignment with instructional goals. New attributes included star ratings, radio buttons, and drop-down menus, each of which can be optionally enabled and disabled by the author.
Idea entries are displayed in a table and sortable by attribute. Entries can also be manually reordered within the table.	Allows students to easily find ideas and to consider them relative to other ideas based on their attributes.	It is overwhelming for students to sort through more than several ideas at a time.	Unit authors can filter the ideas available to students at particular points in the unit, based on the attributes of those ideas. For example, at certain steps, authors determine that students should only see and work on organizing the subset of their ideas that were added on a specific earlier step.
Students drag ideas from their baskets and organize them in a given space. Only one instance of an idea can be present within the space.	Encourages students to make decisions about the distinctions between their ideas.	When students believed an idea was relevant to more than one category, they felt forced to chose one category in which to place the idea, or else they positioned that idea over the line between categories. This added ambiguity to research analyses.	Students can drag more than one instance of the same idea onto the organizing space.

TABLE 1 (CONTINUED)

FEATURE	RATIONALE	FINDINGS FROM IMPLEMENTATION	DESIGN SOLUTION
Revising Ideas			
Students can remove ideas from their Idea Baskets. Removed ideas are accessible in a list that students can choose to show or hide. Students can also restore individual ideas to their baskets from the list of removed ideas.	Gives students a way to remove ideas that they no longer feel are relevant or correct; provides a trace of their prior ideas, and the option to reconsider and revert to previously discarded ideas.	Students rarely removed ideas from their baskets. This may reflect the difficulty students experienced in letting go of ideas in which they had intellectual investment.	Embed occasional prompts for students to clean up their Idea Baskets.
Idea entries remain editable from within the Idea Basket dialog box and at any point during a unit.	Provides students with multiple opportunities to revise their thinking.	Students needed the ability to edit their ideas while in the process of constructing explanations.	Allow students to edit idea entries from within Explanation Builder steps in addition to within the Idea Basket dialog box.
Reflecting on Ideas			
Ideas in the basket are always accessible via an icon in the toolbar.	Facilitates students' task of monitoring and revising ideas.	Students were not always compelled to visit the Idea Basket of their own accord.	Embed occasional prompts for students to access the basket and revise their ideas.
A dedicated Idea Basket step type that authors can insert amid other steps in a unit to remind students to revise ideas.	Confronts students with the full range of their ideas and encourages them to revisit and update their thinking.	Students grew tired of visiting their baskets when prompted too frequently to use them.	Limit Idea Basket prompts to a small number of critical junctures in the unit.
Explaining Ideas			
Contents of the Idea Basket are visible in a side panel of the Explanation Builder's organizing space.	Allows students to easily refer to their available ideas when constructing explanations.	It was difficult for students to sort through all ideas added up until the point of an Explanation Builder, especially when certain ideas were more/less relevant at different points in a unit.	Authors can specify a subset of ideas (based on particular attributes) to make accessible for students to organize on given Explanation Builder steps.
Students can drag ideas onto the organizing space directly from the side panel view of their basket, and move those ideas freely around within the space.	Facilitates students in organizing and distinguishing their ideas.	Within the side panel view of the basket, idea attributes (e.g. ratings, sources) were not visible, and could therefore not inform students' sorting decisions.	Allow authors to select one attribute to display as a column beside idea entries within the Explanation Builder step.
Allow students to set colors for ideas in the organizing space.	Gives students choice in how to mark distinctions between ideas.	Students seemed to choose colors for aesthetic rather than conceptual reasons.	Embed prompts for students to use specific colors for conceptual or organizational purposes.
The background image within the Explanation Builder's organizing space is authorable.	Allows authors to specify structures and categories to guide students in organizing their ideas.	Students' ideas were sometimes too numerous to fit within the organizing space without overlap. Some ideas became concealed by others, and difficult for teachers and researchers to view.	Increase the pixel dimensions of the organizing space.
The prompt field within an Explanation Builder step is authorable.	Allows authors to specify a question for students to answer based on their organized ideas.	Students sometimes overlooked answering this question before advancing in the unit.	Move the field from the bottom to the top of the Explanation Builder space, and allow authors to decide whether to require a student response before allowing students to advance in the unit.

TABLE 1 (CONTINUED)

FEATURE	RATIONALE	FINDINGS FROM IMPLEMENTATION	DESIGN SOLUTION
Sharing Ideas			
Students can choose to make specific ideas available to their peers via a public Idea Basket; and can select and add peers' public ideas to their own private baskets.	Gives students the experience of being a part of a knowledge building community in which they can learn from and build on one another's ideas.	Students appeared to either not be motivated or intentional in sharing ideas. According to analyses of students' recorded conversations and teachers' reports, students sometimes simply skimmed the list of ideas, and rather than thoroughly consider their options, they tended to select ideas with which they already agreed.	Embed prompts with specific criteria to guide students in sharing and selecting ideas within the Public Idea Basket (e.g., Share at least two ideas that you feel are most useful for explaining how cancer treatment works. Select at least one idea from the Public Basket that is different from your own ideas).
Public ideas are anonymous.	Encourages students to develop criteria for evaluating ideas rather than judge ideas based on personal knowledge of their source peer.	Teachers reported that students were conscientious about reading and understanding their peers' ideas when the sources of those ideas were anonymous. This is in contrast to how students usually assume ideas are good when these ideas are known to come from the classmates they perceive to be smarter. However, students were curious to know how their ideas were received by their peers.	Next to each entry in the Public Idea Basket, display the number of times that entry was copied by others.
Supporting Curriculum Integration			
The tool and its components are given the names Idea Manager, Idea Basket, and Explanation Builder.	Gives users a way to refer to the tool and its components.	Unit authors found the IM components' default names constraining. They sometimes had difficulty fitting these names into their units' narratives such as to be appropriate for different target learners.	Components of the IM can be renamed by authors, which facilitates the tool's adaptation for multiple different purposes.

relevant. These and other features proposed by individual researchers for specific purposes and within particular units ultimately became available for use by other unit authors and researchers.

Members also shared strategies for integrating the IM into units. For example, McElhaney, who reflected on the observation that students struggled to deal with the information that accumulated in their Idea Baskets over time, shared a strategy that other authors began to also use, which was to occasionally prompt students to refine or remove ideas from their Idea Baskets with the goal of having these reflect their current thinking. Because the IM's authoring tools allow customized unit integrations, researchers could learn from unit authors' different approaches. As we observed the strategies taken, we discussed which appeared more or less promising, and in what situations. These cases have become a source of design patterns that guide other authors in integrating the IM into their units.

From a Private to Public Idea Basket

Feedback from the teachers, who taught units featuring the IM, as well as our own assessment of the literature on the benefits of collaborative learning, suggested that the next release of the tool should allow students to share ideas with their peers. While we had notions for how collaboration should work, and were excited by the prospect of using this tool to better understand student collaboration, we were also faced with many questions about how we would coordinate those collaborations. Should ideas be anonymous? Should students receive recognition when their ideas are taken up by their peers? Should idea exchanges be moderated by a teacher or researcher, or left to occur without interference?

To explore ways to incorporate the idea sharing feature, we distributed an online survey (https://sites.google.com/site/technologydesignsurvey/) to the wider community of WISE users, which included researchers from other institutions (Matuk et al., 2013). In the survey, we announced plans to incorporate collaborative features into the IM, and through closed and open-ended questions, we solicited respondents' experience-based opinions on how we might proceed. At the same time, we tested our ideas for supporting students' learning from one another by organizing face-to-face idea exchange activities. That is, after students had added ideas to their private baskets during their work on a chemistry unit, we asked them to partner with another student workgroup to view, discuss, and exchange ideas (Matuk et al., 2013).

Ultimately, we created the first version of the Public Idea Basket through the same Agile approach taken with the first version of the Idea Basket: By first building a basic working version that we would later refine through a series of classroom trials. This new version of the IM allowed students to add selected ideas at any time to a public basket, to which students could toggle from their private baskets. Once there, students could copy any public idea into their private baskets, allowing it to become part of their individual repertoires of ideas (see Figures 2A and 2C). This sharing feature allowed us to investigate questions about how students evaluate and incorporate their peers' ideas into their own work (Matuk & Linn, 2014), as well as how technology might be used to support collaborative learning (e.g., Matuk & Linn, 2015).

Determining the Teacher's View of the Idea Baskets

Another feature requested by teachers was for the ability to see the contents of students' Idea Baskets. During summer workshops, researchers and teachers discussed possible ways to display students' IM work in the WISE grading interface. From these discussions, we learned that teachers had different ways of using the IM to support their instruction (Matuk, Gerard, Lim-Breitbart, & Linn, 2015). Some teachers wanted to know how students' ideas were developing before those students proceeded too far in a unit. These teachers were frustrated that the first version of the IM had no interface for them to monitor their students' ideas, nor to send their students helpful guidance as they might have otherwise done. Other teachers were more concerned with students' final explanations, and wanted to leave students with an unmonitored space in which to freely generate ideas without the feeling of being assessed. For those teachers, the ability to monitor students' ideas would rather fulfill a logistic role of making sure students were on task.

Ultimately, we identified two basic pieces of information that a grading interface could provide that would be most useful for all: (a) how much are students using the tool? and (b) are students on task? We integrated information that would help teachers answer these questions within the same

FIGURES 4A-C. The Idea Manager from the teacher's point of view.

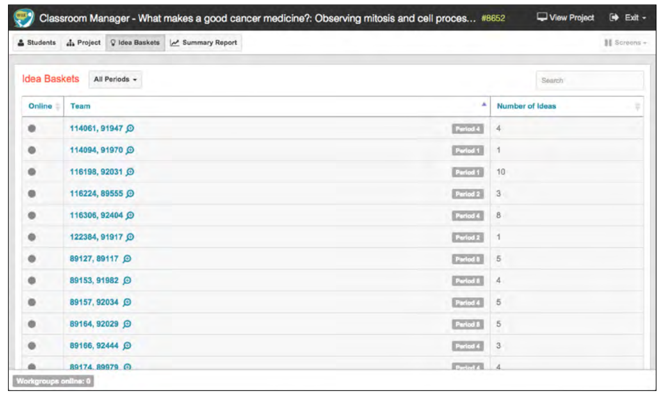

FIGURE 4A. The number of ideas in each student workgroup's basket.

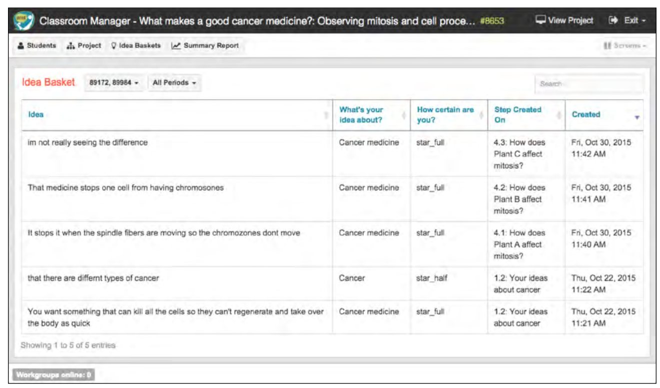

FIGURE 4B. The contents of an individual workgroup's basket.

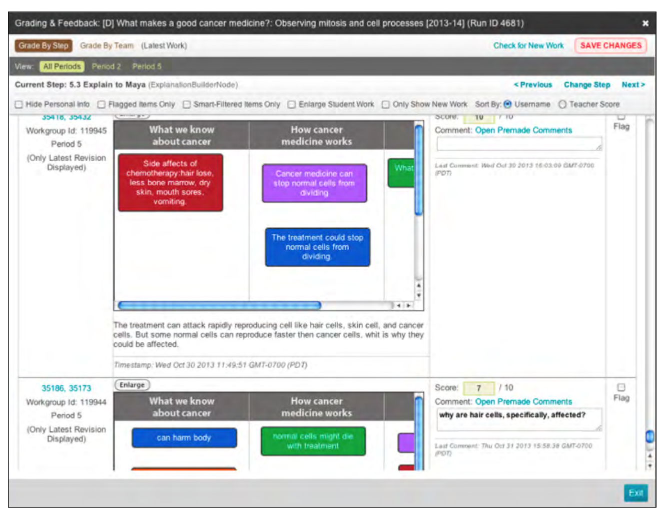

FIGURE 4C. How students organized ideas in an Explanation Builder step.

FIGURES 5A-B. Screenshots from the high school physics unit, Designing a Safer Airbag.

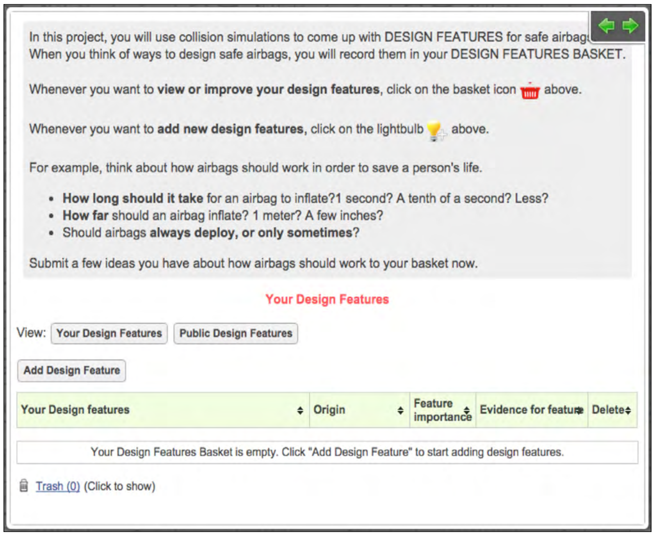

FIGURE 5A. how the Idea Manager is introduced at the beginning of the unit.

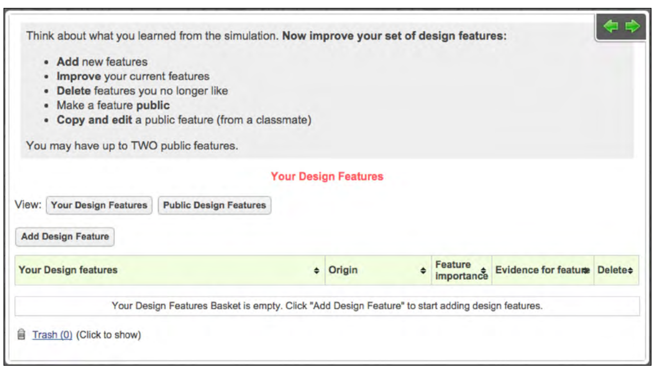

FIGURE 5B. How students are prompted to revise and share their ideas

grading interface that teachers use to access students' other work in a unit. Thus, an overview screen shows a table with a real-time number of ideas in each student workgroup's basket (see Figure 4A). On clicking any of these workgroup rows, teachers can navigate to a view of the contents of that work group's basket (see Figure 4B). There, each idea entry is associated with the step on which it was added, the time at which it was added, and also the tags, keywords, and ratings students assigned to it. Teachers can also view and comment on students' Explanation Builder work, including their final explanations (see Figure 4C).

Specifying the Idea Manager's Integration Into WISE Units

The IM's design not only includes the functions of, and interactions among, the tool's components; it also includes

FIGURES 6A-C. The Explanation Builder step.

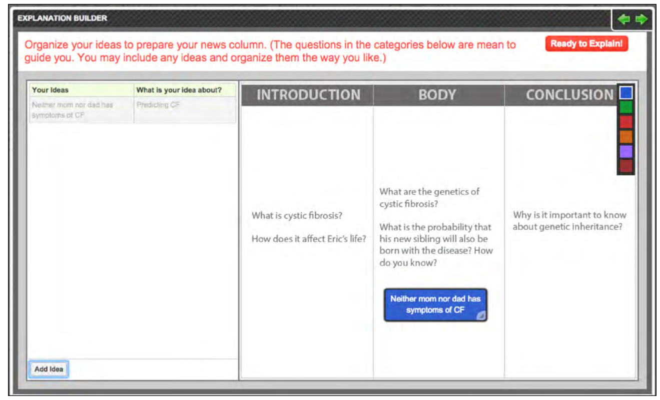

FIGURE 6A. A grade 7 genetics unit, *Simple Inheritance*.

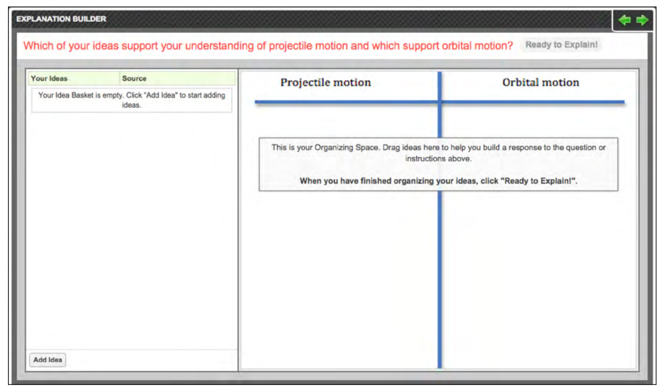

FIGURE 6B. A high school astronomy unit, *Orbital Motion*.

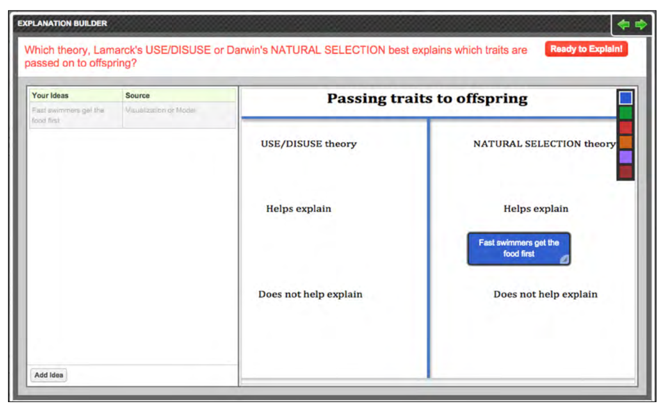

FIGURE 6C. A middle school evolution unit, *Ocean Bottom Trawling*.

the tool's integration into an existing teaching and learning platform. Through implementation of multiple different units featuring the IM, we have begun to refine a generalizable pattern for the tool's integration that includes: framing its purpose, prompting its use, and specifying frameworks for organizing ideas. We discuss these components below.

Framing the purpose of the IM

The IM is introduced to students early on in a unit in a manner that contextualizes and motivates its use. Some researchers have used it as a scientist's lab book for articulating and documenting insights, observations, or "Eureka Moments." Others have had students use the IM to prioritize *Design Features* for engineering projects (see Figure 5A). Still others have used it is a journalist's notepad for collecting information that they would later use to compose a story (see Figure 6A).

Prompting the use of the IM

We had predicted that students would favor their physical notebooks to their Idea Baskets for documenting their ideas, and even then, would require reminders or some external motivation (e.g., an upcoming test). While this was sometimes the case, we also observed that certain students populated their basket with numerous ideas, which quickly became unwieldy. To address these issues, we incorporated occasional reminders throughout a unit for students to use the IM (see Figure 5B), and the ability for unit authors to filter students' baskets so as to make only the most relevant subsets of ideas available at particular steps.

Frameworks for organizing ideas

The Explanation Builder allows authors to specify different ways they would like students to categorize ideas. Categories are typically chosen by the author, and involve determining the dimensions along which ideas might be distinguished to help students in constructing their explanations. Depending on a unit's driving question, the categories might have students distinguish between evidence that supports opposing claims (e.g., that detergent molecules should have polar vs. nonpolar properties; or that evolution is Darwinian vs. Lamarkian). They might have students weigh the advantages and disadvantages of observed outcomes (e.g., positive vs. negative effects of cancer medicine A vs. B vs. C). The categories might also allow students to rank ideas in terms of their helpfulness for explaining a phenomenon (see Figures 6A-C).

INSIGHTS AND AREAS FOR IMPROVEMENT

Our classroom trials show encouraging findings in support of our design decisions. For example, we found that in providing students with ways to annotate their ideas (e.g., specifying the source, rating, and tagging), the IM captures the process of idea generation in a more precise manner and at a finer grain size than is possible with typical embedded assessments such as open ended explanation prompts (Matuk & King Chen, 2011). We also found the IM to support researchers in understanding which students may struggle with which ideas, and when in the process of explanation they may need more support (McElhaney et al., 2012). Finally, we have found that the tool enabled us to investigate ways to structure students' sharing of ideas that most benefit their learning (Matuk & Linn, 2014, 2015). Together, these findings have supported and extended our understanding of knowledge integration, and resulted in implications for the design of the tool's integration into units (see Table 2).

Our experiences with implementing the IM have also revealed several areas for design improvements, which we describe below.

Handling Information Overload

We set out to help students manage the large amounts of information they typically encounter in science. However, by documenting both students' own ideas and those of their peers, the IM ultimately created yet another source of information for students to manage. The many ideas now accessible for students' consideration underscored the need to support students in critically evaluating these ideas. As we continue to refine the design, we are exploring better ways for students to find information that is relevant and that advances their thinking. Future iterations of the tool could include features that allow more targeted ways for students to sort through and filter ideas.

Seeking a Scaffolding Strategy That Does not Attempt to be One-Size-Fits-All

While the IM was intended to promote students' reflection by breaking down the process of explanation into smaller tasks, some students and teachers commented that the prompts to use it, which, in our first implementations could sometimes occur 5-6 times within a week-long unit, felt repetitive. These students came to regard the task with less concern, or neglected adding ideas altogether.

Even when we streamlined the IM's integration so that students were prompted to use it only once, or only at culminating points in a unit's narrative, some students still felt that articulating ideas to include in an explanation was tantamount to writing the explanation itself. It was clear that the pattern of adding, sharing, revising, organizing, and explaining ideas, which we had come to integrate into our units, was more and less helpful for different students. In fact, while we have found that students show greater learning gains when they use the IM to seek ideas from their peers that differ from their own (Matuk & Linn, 2015), we also suspect that those students who are inclined to select peers' ideas that are redundant with their own may be doing so because they have already understood the unit's key ideas (Matuk & Linn, 2014). We continue to seek ways to encourage students' ongoing reflection on the process of explanation, as well as better ways for students to take advantage of their peers' ideas to advance their own thinking. Scaffolding the IM may elaborate upon WISE's existing automated scoring technologies, which currently inform automated feedback to students, based on embedded assessment

TABLE 2. An overview of classroom-based research studies conducted with the Idea Manager, and the implications of their findings for the tool's later design and implementation.

STUDY ***UNIT (GRADE)***	**RESEARCH QUESTIONS/GOAL**	**RELEVANT FINDINGS/OUTCOMES**	**DESIGN IMPLICATIONS**
MATUK & KING CHEN (2011) *Seasons* (9)	How does the IM show where students' ideas come from?	Students generate more ideas from visualizations than from other step types. The physical act of organizing ideas into categories prompted student partners to discuss, reflect upon, and evaluate new ideas in relation to existing ones.	Make use of the IM to support students in understanding complex ideas (e.g., have students use the IM when interpreting visualizations).
McELHANEY ET AL. (2012) *Recycling* (9)	What concepts do students find more/less difficult to grasp and integrate into coherent explanations?	For low prior knowledge students, ideas about molecular bonding were as easy to identify as ideas about structure, but more difficult to integrate into an explanation. This finding demonstrates the IM's ability to identify which students might need more support, with what ideas, and when in the process of explanation.	Use the IM to support students in distinguishing between critical, challenging ideas in a unit. Check in with students' at each step in their process to identify the need for support.
TATE, FENG, AND McELHANEY (2016) *Genetics* (7)	How can the IM help students construct coherent mechanistic explanations of trait expression based on dynamic models?	The IM can provide researchers and teachers with specific information on the nature of gaps in students' mechanistic explanations and their ability to use genetics models.	
MATUK ET AL. (2012) *Recycling, Detergents, Seasons* (9)	Outline the design rationale for the IM with examples from its earliest classroom implementations.	Illustrates ways of integrating the IM into units with different driving questions, and some possible ways that the Explanation Builder can structure students' explanations.	Given a unit's driving inquiry question and learning goals, consider how to best use the categories within the Explanation Builder to provide organizational structure to students' explanations.
MATUK ET AL. (2013) *Detergents* (9)	Describe how we prototyped and tested early design options for a public basket.	Encouraging students to exchange ideas with one another can be a valuable learning opportunity for some, but aimless for others who have not found good criteria for evaluating ideas.	Provide students with guidelines on what ideas to attend to when they visit the public basket.
MATUK & LINN (2014) *Mitosis* (7)	How do students share ideas through the public basket? How does the diversity of students' private ideas change with access to a public basket? What relationship does idea diversity have on the quality of students' explanations?	Students generate more of their own ideas than they copy ideas from their peers. Students are able to recognize and select high quality ideas from their peers. Students who selected peers' ideas that were redundant to their own tended to also write more coherent final explanations. This finding raised questions about whether incorporating redundant ideas supported students in refining their own understanding, or whether students who selected redundant ideas had simply already identified the key ideas necessary to write a coherent explanation.	In deciding whether and when to prompt students to seek public ideas, consider the unit's conceptual scope and complexity, as well as the point in the unit at which students will encounter their peers' ideas. Will the public basket contain ideas that are not superfluous, but that potentially deepen and extend students' own thinking?

TABLE 2 (CONTINUED)

STUDY *UNIT (GRADE)*	RESEARCH QUESTIONS/GOAL	RELEVANT FINDINGS/OUTCOMES	DESIGN IMPLICATIONS
MATUK & LINN (2013) *Mitosis* (7)	Describe the integration of the IM into a revision of an existing WISE unit.	Features that enable the IM to both scaffold and assess include its ability to be integrated into authentic processes of scientific inquiry; to support students to become more reflective of the inquiry process by breaking that process down into deliberative steps; and its ability to record information on students' uses of the tool during a task, and to thus provide more valid evidence of the skills and understanding that students develop.	Align IM-related activities, such as documenting and organizing ideas, with inquiry-related processes, such as observing and distinguishing ideas.
MATUK & LINN (2015) *Mitosis* (7)	What impact does prompting students to seek peers' ideas that are different vs. similar to their own have on learning?	Students' perceived their peers' ideas to have had less influence on their own thinking than is apparent from the way students revised their explanations following a visit to the public basket. Students prompted to seek peers' ideas that were different from their own demonstrated higher learning gains by the end of the unit.	Encourage students to seek peers' ideas that diversify their own, and to reflect on how these ideas impact their thinking.
MATUK ET AL. (2015) *Mitosis* (7), *Detergents, Seasons, Recycling* (9)	Describe how we engaged teachers in specifying design requirements for the IM's grading interface.	For their purposes, teachers were most interested in knowing the number and contents of the ideas students had documented in their baskets.	The top-level view in the general grading interface now includes information on the number of ideas in students' baskets. On clicking, teachers can access a list of the ideas contained in individual baskets.
WICHMANN ET AL. (2014, 2015) *Photosynthesis* (7)	How do students critique peers' ideas with which they agree vs. disagree?	Students generally hesitate to critique their peers' ideas, even those with which they disagree. However, students are more likely to offer suggestions for improving peers' ideas with which they disagree as opposed to ideas with which they agree.	To enable students to gain the most out of peer critique activities through the IM, offer students a model of critque, and lead them to critique ideas with which they disagree.

performance. Through similar adaptive features, students might receive targeted prompts, idea recommendations, and tailored activities based on computer-automated analysis of their existing ideas.

Incorporating More Active Roles for Teachers

On other items in a typical WISE unit, teachers can send comments to students on their work and review revisions made in response to their guidance. The IM, however, offers no similar way for teachers to offer guidance or to participate, instead, it provides an unmonitored space for students to freely add and exchange ideas. Among our plans for future versions is the ability for teachers to comment on students' individual and collective ideas, to suggest ideas for their consideration, or even to allow teachers to seed the public basket with ideas they wish for their students to use.

Enriching Peer Discourse Around Idea Sharing

Within the public Idea Basket, students simply see the number of times ideas have been copied. We are exploring ways to promote richer discourse within and around the Idea Basket through features that allow students to comment upon ideas; to articulate agreement, disagreement, responses, and justifications (e.g., We chose/shared this idea because…); and to publicly cite and build upon specific ideas from classmates in the manner of peer review among professional scientists.

Motivating Authentic Use of the IM

The many different stakeholders involved in the IM's design offered different motivations for students to use the tool. As educators, we wanted to promote students' continual reflection and to give them multiple opportunities to revise their thinking. As researchers, we wanted the fine-grained data that the IM would capture so that we could better describe and understand students' processes of explanation. In our enthusiasm to have students use the IM, its first unit integrations failed to consider how to motivate its use in ways that are as meaningful to students as they were to us. We continue to explore ways to incorporate the IM that make its use integral and necessary for accomplishing a unit's goals. For example, as opposed to framing the IM as a way to support students' progress toward the end of a WISE unit, we might frame the goal to be to seek evidence in the unit to populate the basket.

REFLECTION

The Co-Evolution of Design and Research Goals

The nature of our design context and of our team's membership led to a tandem emergence and co-evolution of the tool's design and of our associated research plans. This emergence is largely due to the need for the IM to be a multipurpose tool that would simultaneously serve the needs of learners, teachers, and researchers. The IM was designed to be integrated into different curriculum units, both new and existing, and to fit within an established learning environment, which already has an instructional delivery system, a teacher portal, and an authoring environment. It was also designed to advance an existing research agenda, with classroom-tested units slated to be enhanced with the tool's integration, and to thus clarify for us the ways that students make sense of science, and where and how they might benefit from instructional support. As such, decisions about the IM's design were closely guided by the Knowledge Integration perspective on curriculum design, as well as by a deep understanding of the context in which the tool would exist.

The Idea Manager represents a specific case of a design-based research approach, which emphasizes the co-evolution of educational design and theory through iterative trial and refinement (Design-Based Research Collective, 2003). Our design process was closely guided by a theoretical framework, and at the same time, shaped by the emergent goals of different stakeholders. While we began with a rough idea of the purposes for which the IM would be used, we settled emergent questions through empirical investigation. We intentionally relied on users beyond our group to demonstrate the tool's potential uses, and to inform further refinements through their experimentation. Reflection upon and across these implementations served to inform new ways that the tool might be used, and have revealed needed features that could not have been foreseen prior to implementing the tool.

Through our process, we have come to better appreciate the importance of having a guiding theory when designing tools for flexible use. Using the Knowledge Integration framework has allowed us to maintain focus on a research agenda even as we proceeded in an intentionally open-ended manner. Moreover, designing the IM to be flexible and adaptable allowed our theory to change and evolve. We have been able to both observe and experiment with the IM's multiple uses, and as a result, we have been able to explore ideas in curriculum design, research, teaching, assessment, and learning in ways that would not have otherwise been possible.

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