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Knowledge Integration and Wise Engineering

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Abstract

Recent efforts in engineering education focus on introducing engineering into secondary math and science courses to improve science, technology, engineering, and math (STEM) education (NAS, 2010). Infusing engineering into secondary classrooms can increase awareness of and interest in STEM careers, help students see the relevance of science and math in their everyday lives, and increase STEM literacy. This paper describes how the knowledge integration framework provides research-based guidelines to help secondary students develop and connect science and engineering concepts. Results from technology-enhanced curriculum units demonstrate how instruction based on knowledge integration principles and patterns using the Web-based Inquiry Science Environment (WISE) can infuse engineering into existing secondary science classrooms. This paper explores how the knowledge integration framework can guide curriculum development and assessment of engineering concepts and habits of mind.

Keywords: curriculum design, technology-enhanced instruction, integrating science and engineering, assessment

In a recent speech announcing a new educational initiative to "Change the Equation," President Obama declared, "[L]eadership tomorrow depends on how we educate our students today–especially in science, technology, engineering, and math" (Obama, 2010). In addition to the President's initiative, much effort is needed to improve science, technology, engineering, and math (STEM) education (NAS, 2010). Introducing engineering into secondary classrooms has the potential to make science and math relevant to students, increase STEM literacy of students, increase awareness of STEM professionals, and increase interest in STEM careers (Katehi, Pearson & Feder, 2009). With these possibilities in mind, the National Academy of Engineering (NAE) convened a workgroup to explore national K-12 engineering standards to accompany math and science standards (NAE, 2010). However, the final report did not suggest specific standards. Citing a lack of engineering experience in K-12 settings and lack of evidence regarding the impact of similar standards-based reforms, the report concluded

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Table 1
Research Questions to Be Investigated to Improve K-12 Engineering Education

- How do children come to understand (or misunderstand) core concepts and apply (or misapply) skills in engineering?
- What are the most effective ways of introducing and sequencing engineering concepts and skills for learners at the elementary, middle, and high school levels?
- What are the most important synergies in the learning and teaching of engineering and mathematics, science, technology, and other subjects?
- What are the most important considerations in designing materials, programs, assessments, and educator professional development that engage all learners, including those historically underrepresented in engineering?
- What are the best settings and strategies for enabling young people to understand engineering in schools, informal education institutions, and after-school programs?

From *Standards for Engineering Education* (2010).

that standards are not the solution. Instead, the report called for infusing engineering ideas into existing K-12 courses, investigating core ideas in engineering appropriate for K-12 learning, creating guidelines for K-12 engineering education materials, and conducting research on learning that can inform engineering education (Table 1).

To achieve these goals, the field needs coherent research on how K-12 curricula can affect learning of science and math principles as well as engineering concepts and habits of mind such as systems thinking, creativity, optimism, collaboration, communication, and attention to ethical considerations (Katehi, Pearson & Feder, 2009). This article describes how instruction based on the knowledge integration (KI) framework using the Web-based Inquiry Science Environment (WISE) can help students develop and integrate science and engineering ideas. Knowledge integration offers a unified framework of research-based guidelines for curriculum design and assessment that can help connect and clarify K-12 engineering education efforts. We draw on two technology-enhanced curriculum units in WISE, *Airbags: Too Fast, Too Furious?* and *Chemical Reactions*, as examples to describe how curriculum designed with KI principles can help students connect and learn science and engineering concepts.

Through these two examples, we demonstrate how engineering can be infused into existing K-12 classrooms. We draw upon these findings to suggest core concepts of engineering appropriate and accessible to secondary science students. We discuss how research using the KI learning perspective can inform engineering education research, and identify guidelines for teaching and learning engineering design based on the KI framework.

Two Examples

This article highlights two curricular units, *Airbags: Too Fast, Too Furious* and *Chemical Reactions,* to describe in detail how the KI framework in combination with the WISE platform helps students connect engineering principles and science content. *Airbags* guides students through an investigation of airbags safety in car collisions (McElhaney, 2010; McElhaney & Linn, 2008). The project encourages students to think as engineers by conducting experiments to explore how the designs of cars and airbags can keep passengers safe on the road. Students connect these ideas to physics and math concepts by integrating their understanding of motion and graphs with car safety. *Airbags* uses a series of scaffolded dynamic visualizations to help students explore the relationship of one-dimensional motion to characteristics of position and velocity graphs. Students experiment with visualizations that provide simultaneous graphical representations and animations of airbag and passenger motion. The results of these experiments serve as evidence for students to suggest improvements to the design of airbags and cars (Figure 1).

In *Chemical Reactions,* students investigate how energy and chemical reactions relate to climate change, and use these chemistry concepts to recommend solutions to decrease carbon dioxide emissions on a global scale. Students explore the greenhouse effect and combustion reactions using visualizations and molecular simulations. Students connect ideas such as conservation of mass, stoichiometric ratios, and limiting reactants to everyday ideas such as driving and electricity use. Students distinguish math and chemistry ideas such as coefficients and subscripts and link these chemical symbolic representations to what they mean on a molecular scale. Students use their chemistry understanding to choose a particular solution to mitigate carbon emissions and create a policy brief to submit to their local congressperson (Chiu, 2010; Chiu & Linn, 2008).

Knowledge Integration and WISE

The KI learning framework builds upon decades of empirical studies on student and teacher learning in K-12 science and engineering classrooms (Linn, 1995; Linn & Eylon, 2006, 2011). KI is a tested, research-based perspective that brings together recent trends in developmental, constructivist, sociocultural, and cognitive perspectives on learning. According to KI, learners build understanding by adding, sorting, evaluating, distinguishing, and refining ideas from classes, everyday experiences, and cultural expectations. KI is based upon a large literature demonstrating that learners come to class with rich, intuitive ideas about phenomena developed from their varied experiences, intellectual efforts, and interpretations of the natural world (i.e., Mulford & Robinson, 2002; Nicoll, 2001; Osborne, & Cosgrove, 1983; Ozmen, 2004; Pfundt & Duit, 1991). These

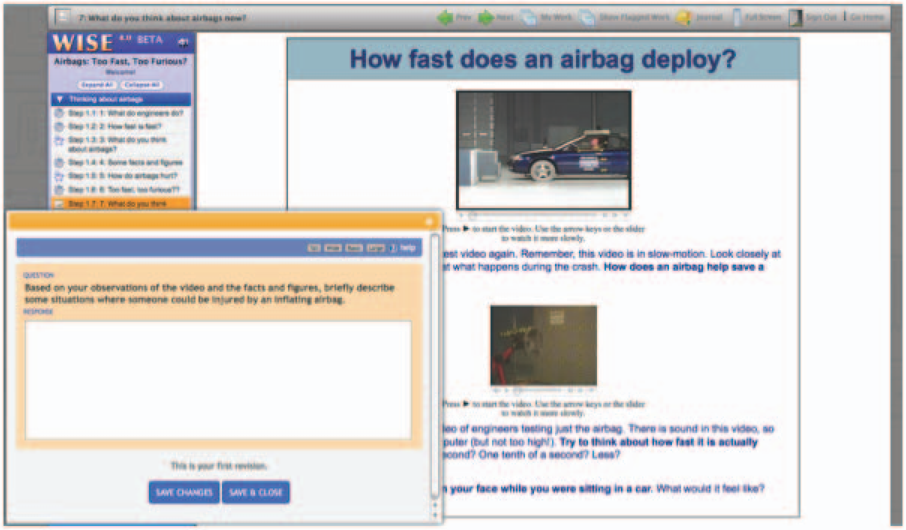


Figure 1. Screenshot of the *Airbags* Curriculum.

diverse ideas serve as a basis for students to make sense of science.

The KI perspective encourages learning by creating opportunities for students to compare, contrast, critique, and distinguish these ideas as well as the new ideas they encounter in instruction. Research on KI shows that students can refine their understanding by considering all their ideas. When students integrate their own views with new ideas they develop reasoning processes that will serve them well throughout their lives.

Typical instruction often focuses on adding ideas but not on helping students integrate new and existing ideas. As a result, students are prone to isolate the new ideas in the context of the science classroom rather than apply new ideas widely. For example, students can learn about projectile motion in physics classrooms and quadratic equations in math classes without any connection between the two. Students can also choose to be cognitive economists, deciding when and where to pay attention or resolve conflicts of ideas (Linn & Hsi, 2000). This happens frequently in STEM classrooms when students do not see the relevance or importance of sorting out their ideas. If students can complete homework assignments and earn passing grades, they may see no benefit to ensuring that their ideas about scientific phenomena are coherent.

To guide instructional designers seeking to promote integrated understanding, researchers have synthesized research findings into the KI instructional pattern. The KI instructional pattern (see Figure 2) identifies the learning processes that are essential for supporting students as they make connections among ideas and develop coherent understanding. The pattern emphasizes several aspects of student learning that are often overlooked in instruction.

Eliciting Ideas

Promoting learning through the KI instructional pattern includes eliciting student ideas. Eliciting existing ideas recognizes the individual backgrounds and experiences that students bring to learning contexts and enables learners to

Figure 2. The knowledge integration instructional pattern encourages students to make connections among their ideas by eliciting, adding, developing criteria, and sorting ideas.

make connections from new instruction to their existing ideas. For example, in a curriculum focused around design of fuels, instruction can prompt students to elicit their existing observations and everyday ideas about energy and chemical reactions.

Adding New Ideas

The KI pattern emphasizes adding new ideas that help students make sense of the topic and connect to their existing ideas. Instruction traditionally places a great deal of focus on adding ideas and concepts through lecture, text, videos, and lab activities. For example, students can add ideas using a molecular visualization of a combustion reaction. Ideally, new ideas fit the criteria of being pivotal cases in that they encourage reconsideration of existing ideas. Pivotal cases are carefully designed comparisons that connect to the beliefs of learners and spur students to seek integrated and consistent accounts of scientific phenomena (Linn, 2005). Pivotal cases are robust over time, help students integrate their understanding in various contexts, stimulate students to apply the cases to different contexts and examples, and help students reason about future investigations and observations.

Distinguishing Ideas

Adding ideas, even pivotal cases, can result in isolated, separate, unresolved, conflicting, and incomplete networks of ideas. To help learners see how their existing ideas relate to, conflict with, or extend these new, normative ideas added during instruction, the KI instructional pattern encourages learners to distinguish among their ideas. For example, students may look at a visualization of combustion and think it is consistent with their view that bond breaking and formation happens instantaneously. Activities to help students distinguish their existing ideas from the new ideas might include prompting students to explain how the molecular view relates to their existing ideas about energy and chemical reactions, to pose critique questions, or to make drawings of their observations. To distinguish ideas, students need to develop criteria for evaluating ideas. These criteria can be deliberately and intentionally developed by self-aware learners, socially constructed in class or communities of learners, or developed by contrasting alternatives. Students need to develop and then to apply their criteria to the group or individual ideas. They will generally need to refine their criteria as well as their ideas about the topic they are studying. For example, when students use their criteria to compare their own ideas to the visualization of combustion, they might need to refine their criteria about chemical bonds. They may also refine their ideas about combustion.

Sorting Out Ideas

Finally, the KI pattern encourages learners to sort out and refine their knowledge based on these evaluations. This includes supporting learners to reflect upon their knowledge, to find gaps or discrepancies in their understanding, and to act to remedy these situations. For example, when asked to write a narrative explaining bond breaking and formation, students might realize that they initially thought that making bonds required energy, but when they added energy in the visualization, chemical bonds were broken. Because their criteria included the relationship between energy and bonding, students might realize that they have conflicting ideas and go back to refine and sort out their understanding. In addition, students might be asked to reflect on the design of an effective fuel. This question might motivate them to reconcile their ideas about bonding and energy with their existing ideas about the design of fuels. Encouraging learners to engage in the full KI pattern supports students to connect their ideas across domains and settings.

Web-based Inquiry Science Environment

The Web-based Inquiry Environment (WISE) has been developed and refined using the KI framework to provide pedagogical features for teachers, researchers, and students to support implementation of the KI pattern (Linn, Davis & Bell, 2004; Slotta & Linn, 2009). WISE is an open-source digital learning platform that supports student inquiry in middle and high school classrooms. Free to the public, WISE enables anyone to develop curriculum and author content such as online brainstorms and discussions, explanation scaffolding, model building, drawing, and online journals (Figure 3). WISE offers a library of tested curricula to implement in classrooms, as well as the ability for teachers, researchers, and developers to take the curricular modules and easily customize them to particular contexts. WISE enables teachers to interact, give feedback, and monitor student work using teacher tools. Teachers can grade student work for a particular step or for a specific student group. Teachers can look on a class dashboard to see individual groups' progress through the project. If teachers see particularly interesting work from certain students, they can check a box to anonymously "flag" the work and put it up on a class screen. WISE provides functionality to researchers such as logging student interactions with the environment at different levels. Embedded assessments enable researchers to capture student thinking during the process of inquiry and design.

Engineering Concepts and Skills Using WISE

The WISE supports for guided inquiry make it possible to incorporate complex engineering concepts such as systems, optimization, and associated habits of mind into the units. Dym et al. (2005) describe crucial engineering design skills such as:

- viewing design as inquiry or as an iterative loop of divergent-convergent thinking;
- keeping sight of the big picture by including systems thinking and systems design;
- handling uncertainty;

Figure 3. WISE guides students' explorations with the inquiry map and uses various step types and tools, such as visualizations, brainstorms, and embedded assessments. WISE offers tools for teachers and researchers to monitor student work, give feedback, customize, and author instruction.

- making decisions;
- thinking as part of a team in a social process;
- thinking and communicating in the several languages of design

This list aligns with the NAE habits of mind: systems thinking, creativity, optimism, collaboration, communication, and attention to ethical considerations (2009). Related design skills include defining the problem, specifying requirements, decomposing systems, generating solutions, creating representations, and experimenting and testing (Petrosino et al., 2008).

WISE is ideal for incorporating engineering concepts and methods in part because an emphasis on engineering concepts reflects the goal of making science relevant, an aspect of KI design. In this article we discuss how these and other engineering habits of mind are being infused into WISE units.

For example, powerful visualizations embedded in WISE curriculum encourage students to engage in systems thinking (Figures 1 and 3). Research suggests that simulations can foster systems thinking and emergent properties in K-12 students (Levy & Wilensky, 2008; Wilensky & Reisman, 2006). The MySystem steps in the *Thermodynamics* curriculum unit enable students to construct their own system maps of energy at various levels (Figure 4; Svihla et al., 2010). Within the *Improving Your Communities' Asthma Problem,* students use visualizations to investigate how the immune system and respiratory system create an asthma attack, and design community-based solutions to improve local asthma problems (Tate, 2009). The *Photosynthesis* unit illustrates energy transfer and transformation using visualizations and virtual experiments (Ryoo & Linn, under review). These and other WISE projects introduce the big idea of systems thinking in the context of standards-based science topics.

In addition, WISE encourages students to collaborate with each other through steps such as online brainstorms and discussion that can be tailored to scaffold students' knowledge integration. These steps enable students to share and build off of each others' ideas in ways that can encourage participation from typically underrepresented populations (Hsi & Hoadley, 1997). For example, in the *Probing Your Surroundings* unit, students create principles to describe patterns in collected temperature data from objects in the room. Based on these created principles, students are grouped in specific online discussion groups to encourage communication and refining of ideas (Clark & Sampson, 2007).

WISE encourages students to develop communication skills in different modalities. In addition to the MySystem concept mapper, WISE drawing tools enable students to make quick and easy animations of their ideas using predetermined pictures or "stamps." The WISE journal allows students to keep an ongoing record of their ideas, incorporate screenshots or animations, and share these journal pages with other students in their class. WISE notes allow students to write explanations of their ideas and revisit and revise these same explanations as reoccurring notes as they progress through the curriculum.

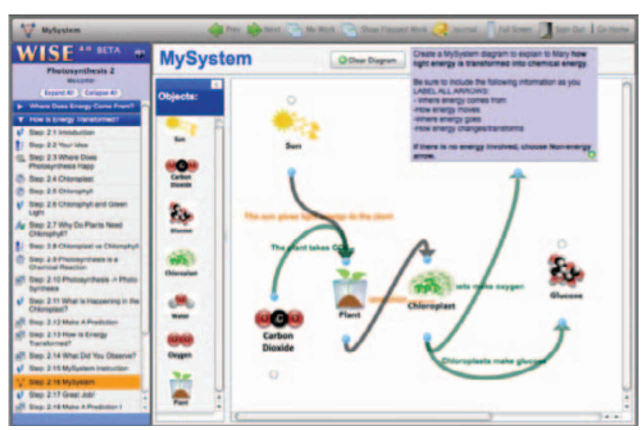


Figure 4. The MySystem step in the Photosynthesis WISE project supports students to make models of energy systems.

Engaging students in relevant, meaningful, and accessible inquiry projects enables them to think like engineers and learn engineering concepts and design skills. *Airbags* and *Chemical Reactions* illustrate these kinds of projects in WISE and demonstrate how students learn science and engineering content.

Airbags

Airbags was designed, iteratively refined, and tested with a partnership of teachers, researchers, and content specialists as part of the Technology-Enhanced Learning in Science (TELS) National Science Foundation Center for Learning and Technology (Kali, Linn, & Roseman, 2008; McElhaney & Linn, 2010). Airbags was designed using KI design principles and patterns (Kali, 2006; Linn & Eylon, 2006). The KI principles (Linn & Hsi, 2000) are guidelines for encouraging coherent understanding in STEM:

Making content accessible encourages learners to build on previous knowledge, connect new knowledge to existing knowledge, and appreciate the relevance of STEM concepts to their everyday lives. The *Airbags* unit makes content accessible by situating force, motion, and position and velocity graphs within the everyday context of driving cars.

Making thinking visible helps students integrate their understanding by modeling how ideas are connected and organized in new knowledge networks. Providing multiple representations of scientific phenomena and highlighting how features of the phenomena interact can make thinking visible. In *Airbags,* students experiment with visualizations that simultaneously present animated and graphical representations of airbag and driver motion. These visualizations also provide students with an experimental history in table format so that their previous trials are visible (Figure 5).

Helping students learn from others encourages students to develop criteria for and refine their own understanding by confronting students with the ideas of others. In *Airbags*, as in all WISE projects, students are encouraged to work in dyads to promote collaboration and peer discussion about the instructed concepts. Grouping students in pairs has been found to be particularly beneficial for the exchange of ideas (Gerard et al., 2009; Madhok, 2006). Students with different levels of expertise work together to help each other learn. A student with less prior knowledge about the targeted concepts often has quite proficient computer skills, or interacts with visualizations and notices different features than his or her partner with more prior knowledge. Students often ask each other to explain concepts or visualizations that they do not understand. This explanation process helps both the explainer and the explainee learn and reinforce the targeted concepts. This kind of peer collaboration fosters knowledge integration.

Promoting autonomy and lifelong learning helps students refine their understanding by encouraging monitoring and reflection upon ideas. Airbags promotes reflection by having students construct a report about the design of cars based on the results of their experiments and investigations with the visualizations. Students reflect on their ideas by refining these design recommendations.

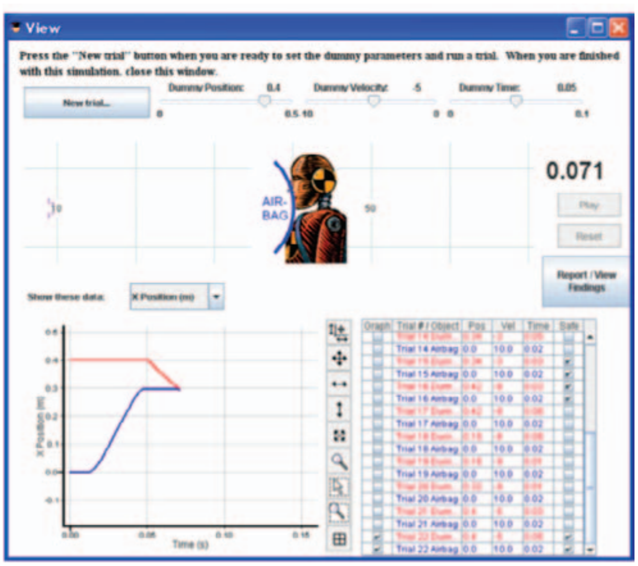


Figure 5. The airbag visualization makes students' thinking visible by providing tables with their experimental history.

Core Engineering Ideas in Airbags

In *Airbags* students encounter systems concepts including: knowing how individual parts or processes within a system work together to carry out a particular function, knowing how to break systems down into subsystems to gain insight into the function and performance of particular parts to the whole, and knowing about the boundaries and interactions between subsystems and system or systems and the environment.

Airbags guides students by breaking down the overall system into its constituent parts. Students first investigate simulations of the airbag and its motion. Subsequently, students explore simulations of the motion of the driver. Students then experiment with a simulation of a driver and the airbag to determine how the two systems interact and safety implications of these interactions (Figure 6). Students are guided to discover different types of relationships among these variables that govern the risk that the driver will be injured from an inflating airbag. These relationships include covariation and thresholds. Driver height, speed of collision, and size of crumple zone all influence the amount of time from impact to the time when the driver and airbag collide. Low speed collisions with tall drivers in cars with large crumpling will be more likely to hit an inflated airbag (more safe). High speed collisions with short drivers in cars with small crumpling will be more likely to hit an inflating airbag (unsafe). However, there are also threshold values for position and time. Short drivers who sit within the airbag's range of deployment will always hit an inflating airbag, and tall drivers who sit beyond the deployment range will hit an inflated airbag. The project guides students to make these kinds of insights about the relationships among variables.

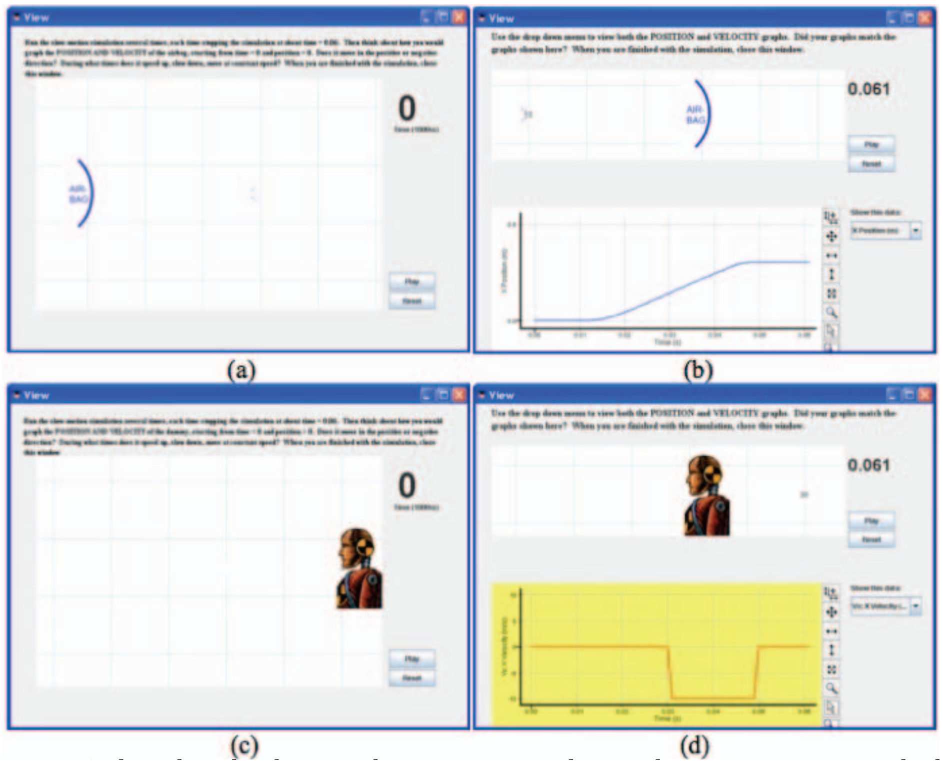


Figure 6. *Airbags* breaks the visualizations into airbag and passenger systems before students experiment with an airbag and passenger visualization.

Optimization involves maximizing effectiveness of a process or system by manipulating variables and taking into consideration trade-offs, available resources, social norms, and physical laws. *Airbags* requires students to consider multiple variables, trade-offs, social norms, and physical laws to make the best decisions in their final reports. The inquiry around airbags provides a rich context for discussing constraints. Airbags must deploy very quickly within a certain amount of time within a very finite space between the passenger and the steering wheel. Students consider these variables to make recommendations to the design of cars and airbags to decrease injuries and fatalities from airbags.

In *Airbags,* the overall driving question and inquiry project engages students in generating solutions and making decisions. Students decide whether black boxes should be designed to produce position or velocity graphs, and explain their choice using what the have learned throughout the project about position and velocity graphs and how these graphs relate to personal safety.

The context of *Airbags* encourages students to collaborate with each other as a team on a problem with social and global implications. Additionally, students learn communication skills through different forms of representation. Students construct graphs of the airbag and driver's motion using drawing tools within WISE and compare these graphs to ones in the simulations.

Students develop experimentation and testing skills by interacting with scaffolded visualizations in *Airbags*. Students use the visualizations to investigate questions about the role of the height of the driver, speed of collision, and crumpling ability in relation to the driver's risk of injury. These questions align with the variables that students can manipulate in the visualization (position of the driver, velocity of the driver after impact, and time between impact and driver's initial motion towards wheel). Students conduct trials to test their hypotheses by first selecting an investigation question from a drop-down menu. This menu also includes a choice for just exploring so that students can familiarize themselves with the visualization. Having students choose a particular question encourages students to be more mindful with their trials and focuses them on the inquiry goals. After students run the trial, they judge whether the trial was safe or unsafe. This, along with the variable settings, is visible within the experimentation history of the visualization. The experimentation history enables students to see patterns within the data and compare multiple trials to facilitate analysis of data and student monitoring of their experimentation.

Airbags Learning Outcomes

The design partnership for *Airbags* developed, refined, and validated assessment items that measured connections among students' normative ideas (Lee, Linn, Varma & Liu, 2009; Linn et al., 2006; Liu et al., 2008; Liu, Lee & Linn, 2010). Embedded, pretest and posttest assessments, as well as year-end benchmark assessments consist of open response items that require students to explain, graph, and draw their understanding. Student responses were scored according to the number of normative ideas and the number of elaborated links among those ideas. The overall KI rubric assigns a score of 0 for irrelevant or blank answers, a score of 1 for non-normative or invalid ideas, a score of 2 for normative ideas lacking connection, a score of 3 for a valid and elaborated link among two normative and relevant ideas, and a score of 4 for complex links among three or more normative and relevant ideas (Table 2).

Students participating in *Airbags* made significant learning gains. Across diverse schools and settings with various levels of student prior knowledge, students make large gains from pretests to posttests assessments (McElhaney, 2010). Students participating in the *Airbags* curriculum made connections among graphical representations and motion concepts, and made significant improvements in their ability to design and interpret valid experiments. These students also outperform similar cohorts of students on year-end tests (Lee et al., 2009). These results demonstrate that curricula engaging students in engineering thinking in science classrooms can foster integrated understanding of both engineering and science concepts.

Chemical Reactions

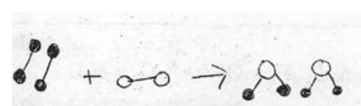
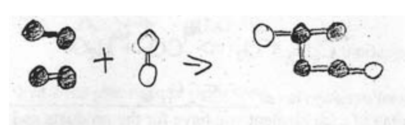
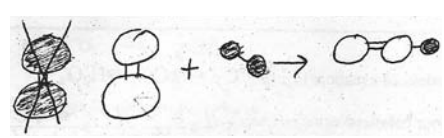
The *Chemical Reactions* project was designed, implemented, and iteratively refined using the same TELS partnership model as *Airbags.* The project also used KI metaprinciples to guide design of the curriculum. For example, *Chemical Reactions* makes content accessible by situating the curriculum within the context of climate change, energy use, and greenhouse gases. *Chemical Reactions* makes thinking visible by providing interactive visualizations of chemical reactions and coordinating these visuals with other representations of chemical reactions, such as videos of hydrogen balloons combusting or symbolic representations (Figure 7). Students make their thinking visible by creating their own models of chemical reactions and the greenhouse effect. *Chemical Reactions* helps students learn from each other through online discussions, where students discuss climate change and are guided to comment on other students' posts. Students then view a video and subsequently refine or add posts to the online discussion. Students also critique each other's final reports and use the feedback to revise their own reports at the end of the project. *Chemical Reactions* promotes lifelong learning by supporting students to reflect upon their learning. Reflective prompts ask students to explain their understanding before and after the students encounter the visualizations. Additionally, students are prompted to reflect upon their understanding at the end of each activity by revisiting their explanations and notes that build towards the final report to their congressperson.

Core Engineering Ideas in Chemical Reactions

Chemical Reactions encourages systems thinking by using NetLogo (Wilensky, 1999) simulations of the greenhouse effect where students break down the greenhouse effect into different interacting components (Figure 8). Students use a scaffolded visualization that includes sunlight, heat, infrared radiation, and a temperature output to gain

Table 2
Example Knowledge Integration Scoring Rubric for Pretest and Posttest Items

Question: If a grey circle represents hydrogen, a white circle represents oxygen, and a bond is represented with a line, draw a molecular picture of the following balanced equation: $2H_2 + O_2 \rightarrow 2H_2O$.
(Possible ideas to integrate: Conservation of mass, molecular understanding of subscripts and/or coefficients, dynamic nature of reaction)

Score	Description	Student Example
4	Complex link: Two or more scientifically valid links among ideas.	
3	Full link: Complete connection among ideas. Students understand how two scientific concepts interact.	
2	Partial link: Partial connections among ideas, students consider relevant ideas but not consistent throught response (i.e. correct molecules but incorrect number)	
1	No link: Students have non-normative links or ideas in a given context.	
0	No/Irrelevant answer: Students do not engage in given science context.	I don't know

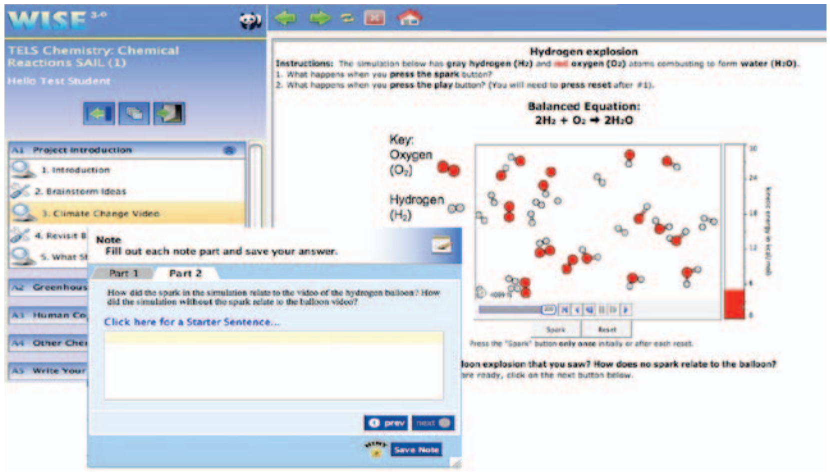


Figure 7. *Chemical Reactions* features molecular dynamic visualizations and supports for students to distinguish their ideas.

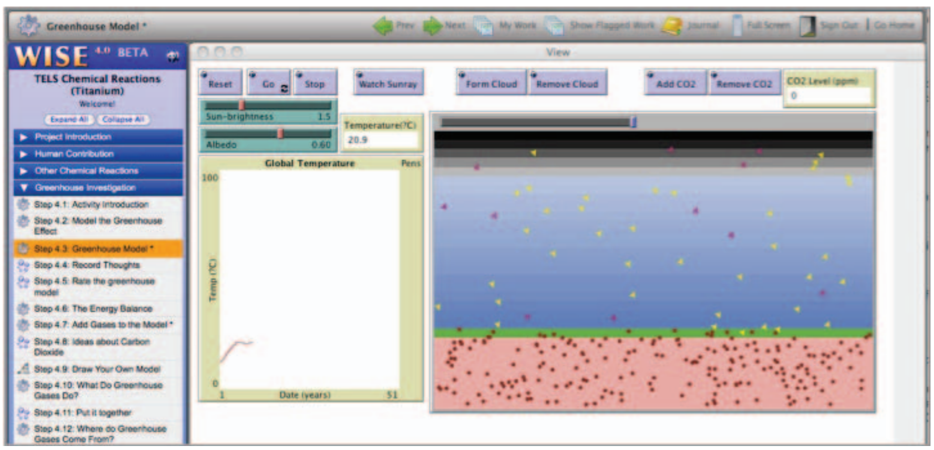


Figure 8. NetLogo greenhouse effect visualization used in Chemical Reactions.

a basic understanding of how sunlight can heat the Earth, and how the Earth in turn emits infrared radiation. They are asked to predict what happens to the Earths' temperature after running the simulation over a period of time. Many students predict that the temperature will continue to rise, or that the temperature will level off but do not understand why. The curriculum guides the students to realize that there is a dynamic equilibrium of energy from the Sun absorbed by the Earth and IR emitted from the Earth. From there, students investigate how other factors such as carbon dioxide, albedo, and population impact this process.

To promote understanding of optimization, students create reports based on the physical processes of the greenhouse effect that take into consideration the social norms and tradeoffs of various solutions. For instance, students investigate the benefits and tradeoffs of switching to alternative fuels, such as hydrogen. Students realize that although hydrogen combustion does not contribute carbon dioxide to the atmosphere, it takes energy to make and store hydrogen fuel, and these sources of energy contribute carbon dioxide to the atmosphere. Students compare these kinds of solutions to other solutions such as raising gas-mileage standards in light of social and scientific efficiency. In these cases, students make decisions about various solutions that do not have a defined right or wrong answer. Students explore problems that have implications to students' everyday lives, like energy use, and connect to social and global issues such as climate change. Students realize that what they are learning in chemistry class can contribute to decisions and recommendations in larger social contexts.

Chemical Reactions engages students in iterations of divergent-convergent thinking as they go through specific activities that culminate in an overall proposal to their congressperson. In each activity students explore a specific topic and relate it back to the overall goal of finding a way to reduce carbon emissions. For example, students investigate hydrocarbon reactions in an activity and use those concepts to understand current sources of energy for cars. In another activity students learn about hydrogen combustion and alternative fuels as possible alternatives to hydrocarbon use. In each activity, students converge on specific topics but then diverge at the end of the activity to relate the principles or concepts that they just learned to the overall investigation.

This interplay between the specific concepts and the overall inquiry helps students to maintain sight of the big picture and overall system while learning subsystems and related concepts. Explicitly referencing back to the overall goals of the project gives students a support structure and frame for them to place specific knowledge and fit how subsystems interact with the larger systems. This helps students maintain sight of the big picture during these inquiry projects. This approach builds upon the success of with previous K-12 inquiry design curricula (Kolodner et al., 2003).

Chemical Reactions promotes collaboration skills by online brainstorms of their existing ideas. The project guides students to read and comment on other groups' postings, and then make another comment of their own. The project encourages communication skills by having students write multiple-paragraph reports that synthesize and convey their understanding. Students create models of the greenhouse effect using drawing tools and construct models of chemical reactions by manipulating atoms and molecules (Figure 9).

Chemical Reactions Learning Outcomes

The design, refinement and validity testing of assessments with Chemical Reactions followed the same partnership and iterative refinement model as *Airbags*. Researchers developed pretest, posttest, and delayed posttest assessments and analyzed the data in accordance to the KI framework. Students across the country in various high schools with various levels of students gained significantly from pretests to posttests, compared to students with traditional instruction (Linn et al., 2006). Students participating in the *Chemical Reactions* unit made connections among concepts such as conservation of mass, limiting reactants, heat, and molecular motion as well as connections among representations. Students also connected and distinguished ideas about chemical reactions, the greenhouse effect, and distinguished the greenhouse effect from climate change. Evidence suggests that these learning gains are robust over time; even though the unit takes only 4–5 hours of instructional time, students outperform their peers on extended posttests months after instruction and in some cases outperform themselves from posttest to extended posttest (Linn et al. 2006; Lee & Linn, 2008).

The results from both *Chemical Reactions* and *Airbags* along with other TELS projects provide evidence that curricula using the KI pattern can help all students learn science and engineering concepts. Both projects were tested at very diverse settings with wide ranges of students. Students not only learn, but also retain their understanding. This suggests that the KI pattern can be a particularly powerful way to introduce engineering concepts into science classrooms. The outcomes also provide evidence that the KI assessment framework is a valuable and reliable tool to measure links among engineering and science ideas.

Guidelines for Engineering Education Curriculum Design

To infuse engineering ideas into the K-12 curriculum, designers need to select contexts for investigation that illustrate complex, realistic situations. Successful activities should require students to use scientific ideas to solve problems in these contexts. To ensure that new scientific ideas are integrated into coherent understanding, activities need

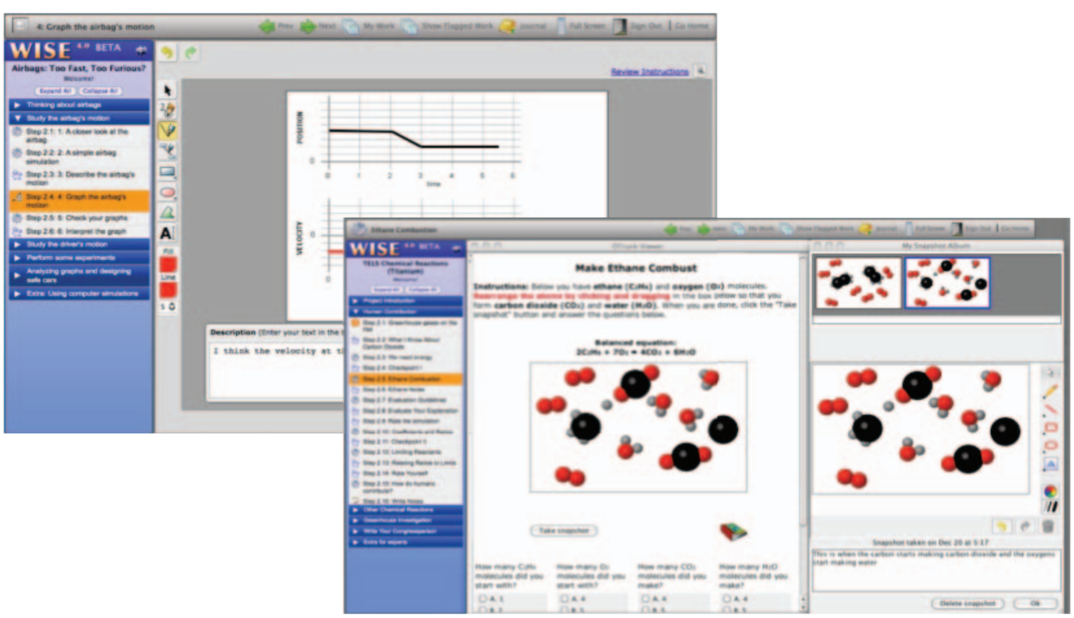


Figure 9. Both *Airbags* and *Chemical Reactions* leverage drawing tools within WISE to support students creating representations.

trial and refinement in classroom settings. The KI pattern, used to design *Airbags* and *Chemical Reactions*, has proven effective for guiding the design process.

Iterative Design and Refinement

Iterative design and refinement based on student learning evidence is essential to ensure that units meet their goals. Both *Airbags* and *Chemical Reactions* were designed and iteratively refined by a partnership of researchers, classroom teachers, technologists, and content specialists. Ideally partnerships will include experts in engineering to certify the validity of the engineering concepts, practices, and habits of mind. The design partnership ensures that these curriculum units are educationally sound, accurately represent important science and engineering concepts, and succeed in authentic classrooms with real teachers and students.

For example, iterative refinement studies of *Chemical Reactions* demonstrated overall learning gains for both honors and regular chemistry students. Studies of the first version revealed that students in regular chemistry were less successful than honors students in interpreting some of the visualizations. The design of the curriculum surrounding these visualizations implemented the predict, observe, explain pattern found to be successful in various science classes (Gobert & Pallant, 2004; Krajcik, Blumenfeld, Marx, & Soloway, 1994; Tien, Teichart, & Rickey, 2007). Students predicted what a chemical reaction would look like on a molecular scale, interacted with the visualization, and then described what happened in the visualization.

To refine the instruction around the visualizations, the partnership used the KI pattern and added a focus on distinguishing ideas (e.g., Linn et al, 2010). Visualizations within *Chemical Reactions* were refined to help students compare and distinguish their ideas. This converted the to predict-observe-explain pattern into predict-, observe-, distinguish-reflect. Students were asked to distinguish ideas about how the chemical formulas related to the chemical reactions. They also considered what symbolic representations do and do not represent about reactions. Students then assessed and reflected upon their explanations. This change required modifying the context of the visualization from the design of rocket fuels to the use of hydrogen fuel to make the visualizations more relevant to the overall inquiry (Chiu, 2010).

This is an example of design-based research where evidence of student learning is used for refinement of classroom interventions and also advances theoretical understanding of learning (e.g. Design-Based Research Collective, 2003). Due to the complexity of authentic learning in classroom environments, interventions need to be tested and carefully engineered with the complete system of teachers, students, and classroom culture to reveal insights into cognition in classroom settings (Brown, 1992). These kinds of design experiments with WISE modules can both improve classroom learning and contribute to learning theory.

In another example, students were randomly assigned to two different versions of *Airbags*—one version explicitly prompted students to isolate and compare variables, while another version explicitly prompted students to connect variables with the underlying concepts (McElhaney, 2010; McElhaney & Linn, 2010). On posttest assessments of overall understanding, students in the connecting concepts condition outperformed the isolate and compare variables condition. This study clarified research on experimentation to demonstrate that merely isolating and comparing variables correctly may not result in greater understanding of concepts. Using design-based experiments, *Airbags* was able to contribute to learning theory, provide meaningful and tested instruction to students, and use the results to make refinements to the instruction and future experiments.

The Knowledge Integration Instructional Pattern

The NAE recommends that engineering education should emphasize the process of engineering design. NAE states that "the design process, the engineering approach to identifying and solving problems, is (1) highly iterative; (2) open to the idea that a problem may have many possible solutions; (3) a meaningful context for learning scientific, mathematical, and technological concepts; and (4) a stimulus to systems thinking, modeling, and analysis" (p. 4). Dym, Agogino, Eris, Frey & Liefer (2005) define engineering design as "a systematic, intelligent process in which designers generate, evaluate, and specify concepts for devices, systems, or processes whose form and function achieve clients' objectives or users' needs while satisfying a specified set of constraints" (p. 104). The KI instructional pattern offers a research-based design guide for creating science units that also emphasize engineering design. WISE provides a learning environment and set of features to turn these principles into practice.

The KI pattern aligns well with the engineering design process. It is composed of four processes: eliciting ideas, adding ideas, distinguishing ideas, and sorting out ideas.

Eliciting ideas. Starting by *eliciting ideas* enables students to build from their prior knowledge. Eliciting a full range of ideas helps students make connections across contexts and disciplines instead of isolating ideas. In the engineering design process, students elicit their ideas by brainstorming and generating a wide range of possible solutions to a design problem. KI research demonstrates that tools such as the WISE online brainstorming tool encourage participation from students who may not traditionally participate in engineering (Hsi & Hoadley, 1997). Holding online brainstorms also enables all students to see everyone else's ideas and revisit these brainstorms throughout the project. Student ideas are visible to both students and teachers.

Adding ideas. The next element of the KI instructional pattern, *introducing new, normative ideas* through carefully designed instruction has the goal of helping students build upon their existing ideas and make connections among these new ideas. In the engineering design process, after students come up with a wide range of possible solutions by brainstorming their ideas, students need to seek out additional knowledge and information about their proposed solutions, including related math and science concepts. In WISE, powerful visualizations enable students to learn about scientific concepts and experiment with ideas**.** WISE also gives students the freedom to learn about ideas as they see fit. Students can choose different topics to learn about in a just-in-time manner. For example, in the Designing House project, students choose to become experts in walls, roofs, or windows. Students can then either jigsaw into groups with different expertise or come back to these topics as they need to during the design process (Cuthbert & Slotta, 2004).

Distinguishing ideas. As mentioned, a crucial aspect of the KI framework is to help students *develop criteria and distinguish among their ideas*. Eliciting and adding new ideas can result in links and connections among ideas or concepts that may or may not be productive. Instruction that guides learners to evaluate their ideas using powerful criteria is needed to help students learn. When students select a certain design solution, they need to evaluate their solutions or ideas using design criteria or set of constraints. Students can use WISE assessment tools to assess and evaluate their own understanding of concepts (Chiu & Linn, 2008; Davis & Linn, 2000). WISE online discussion tools enable students to post designs and offer feedback on each others' designs according to negotiated or given criteria. These discussions can be seeded, or students can be grouped into predetermined topics or levels of expertise, or based on selections that students make.

Sorting out ideas. After learners evaluate their ideas, they need support to *reflect, refine, and sort out the connections among their ideas*. In the engineering design process, after students evaluate their design, they need to reflect upon their initial design and the given evaluations and refine and redesign their solution. These reflective processes have demonstrated benefit to engineering education (Adams, Turns & Atman, 2003). WISE journal tools enable students to make refinements to their designs and log changes between previous experiments and new proposed experiments or designs.

This pattern can guide the iterative design process. Combined with specific design principles (Kali, 2006) and the features of WISE (Slotta & Linn, 2009), this process can help designers create effective precollege activities that feature engineering design concepts and practices.

Discussion

The KI pattern and WISE features provide a way to leverage the natural connections between engineering and science inquiry (NAE, 2010). This article shows how the KI framework can bridge engineering and science topics to support inquiry. For both *Airbags* and *Chemical Reactions* we illustrate ways to showcase engineering principles in science units. Both units resulted in student learning of science content and engineering skills.

Other curriculum materials built for science inquiry have a similar potential. For example, Model-It (Spitulnik, Krajcik & Soloway, 1999; Stratford, Krajcik & Soloway, 1998), Virtual Solar System (Barab, Hay, Barnett & Keating, 2000) and ThinkerTools (White & Frederiksen, 1998) ask students to make, test, and revise models to explain scientific phenomena. To fully succeed, these and other inquiry materials are most successful when they engage students in using the full KI instructional pattern (see Linn & Eylon, 2011).

Instruction that engages students in design tasks, such as Learning by Design (Kolodner et al., 2003), design-based science (Fortus et al., 2004), and Learning-for-Use (Edelson, 2001) have been successfully implemented in K-12 settings. These environments also have the potential of guiding students through eliciting, adding, distinguishing and sorting ideas but often depend on a talented teacher to succeed (Linn & Eylon, 2011).

KI provides a unified framework based on research in learning and cognition that aligns learning theory, curriculum design, and assessment. The KI patterns and principles can provide guidance for the emerging field of K-12 engineering education. Current work with KI and WISE illustrate the power of the KI pattern and suggest ways to refine instruction to promote coherent understanding.

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