Chapter 3

Orchestrating inquiry instruction using the knowledge integration framework

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Introduction

This chapter describes how the knowledge integration framework (Linn and Eylon 2006) can strengthen inquiry instruction. Using the Web-based Inquiry Science Environment (WISE) we designed instruction featuring scientific experimentation to help students gain an epistemologically normative view of inquiry and to support students' understanding of everyday science. We draw on studies using the *Airbags: Too Fast, Too Furious?* unit. The unit helps physics students integrate their understanding of motion and graphs during an investigation of the safety of airbags in car collisions. We report on a series of studies that illustrate how to improve virtual experimentation and at the same time ensure that students gain valuable inquiry skills.

Goals

In this chapter, we describe research that broadens students' views of classroom science. Studies show that students typically sequester their understanding of classroom science from their explorations of science in everyday life (Zimmerman et al. 2010). We draw on research about students' social (Barton 1998) and academic identities (Brown 2006) as well as their experiences in local communities (Corburn 2005) to inform design of inquiry activities. We seek ways to help students integrate their views of science from experiences in diverse settings.

We use the knowledge integration perspective (Linn and Eylon 2006; Linn and Eylon in press) based on over 25 years of research on inquiry science to guide our efforts to make experimentation meaningful and relevant within inquiry investigations. We draw on the views of Lehrer, Schauble, and Petrosino (2001) who argue that the history of experimentation within the authentic inquiry practices of argumentation, representation, and modeling 'imbues the dry bones of experimentation with meaning and significance' (p. 275). We explore ways to engage students in authentic investigations that promote the integration of scientific ideas about the domain, the methods

of investigation and everyday experience. We illustrate ways that inquiry instruction can take advantage of real-world scientific issues to help students test their own ideas, build on everyday experiences, and achieve complex scientific insights.

Rationale

Experimentation is a critical aspect of professional scientific inquiry (Kuhn 1970; Latour and Woolgar 1986; Thagard 1992) and a desired component of school science (National Research Council 2007). Professional views of experimentation are diverse and include, in addition to controlled laboratory experiments, quasi-experiments (Campbell and Stanley 1966; Campbell et al. 1963), natural experiments (Freedman 2005), and design experiments (Brown 1992; Collins et al. 2004), among others. In choosing an experimentation approach, professional scientists must weigh the benefits of different methods and decide which ones align best with the context of inquiry and provide the most valuable insights about the investigation. While scientists' views of the appropriateness of these experimentation approaches may differ, their views regarding the general purpose of experiments are more uniform. Scientists conduct experiments about a wide range of questions using a plethora of methods that often require considerable creativity and cannot be reduced to a set of steps.

Typical school science instruction does little to communicate the nuances of authentic experimentation and their relationships to the context of investigation (National Research Council 2006). Students often follow recipe-like procedures that lead to predetermined outcomes rather than conducting their own investigations. Teachers instruct their students to vary one variable at a time without providing a clear rationale for this procedure. These typical classroom practices can discourage authentic student conceptions of scientific experimentation.

School science standards may also promote procedural views of experimentation. For instance, the California Department of Education (2000) states for middle school, 'Distinguish between variable and controlled parameters in a test' (p. 29) and for high school, 'Identify possible reasons for inconsistent results, such as sources of error or uncontrolled conditions,' and 'Recognise the issues of statistical variability and the need for controlled tests.' (p. 52). Though these standards address important aspects of experimentation, they focus on the validity of controlled experiments rather than on whether they answer an important question or advance understanding. These standards may encourage teachers to focus on the procedural mastery of controlling variables rather than on the nature of scientific investigation. Experimentation tasks that ask students to apply specific strategies misrepresent the nature of scientific inquiry and may preclude robust understanding of scientific experimentation. To develop authentic views of scientific experimentation, students need to explore uncertain situations and test their own conjectures. When students design experiments that test their own ideas and answer relevant questions about the world they can gain insight into science inquiry.

Role of domain knowledge in designing and interpreting experiments

The role of domain knowledge in scientific experimentation has become progressively more central to research on scientific reasoning. Early research addressed children's ability to isolate variables in experimentation contexts where domain knowledge played little or no role in making inferences. For instance, Inhelder and Piaget (1958) designed a task (later adapted by Kuhn and Phelps (1982) and others) that asked subjects to determine what combination of colorless fluids would yield a specific reaction outcome. Siegler and Liebert (1975) examined the ways subjects determined how an electric train runs on the basis of four binary switches (though in actuality, a researcher operated the train using a secret switch to ensure that subjects would test all 16 combinations). These studies examined experimentation as domain-general logical inference. In these situations, subjects could make valid inferences only by isolating variables to logically eliminate possibilities.

Research on experimentation in more knowledge-rich contexts has revealed the important role of domain-specific knowledge in how students conduct experiments. Studies in realistic contexts illustrate how designing and interpreting experiments involves a much more complex and nuanced set of factors than simply the ability to logically confirm or disconfirm hypotheses using controlled experiments. For example, studies show that children are more likely to test plausible rather than implausible hypotheses (Klahr et al. 1993; Tschirgi 1980), focus on variables they believe to be causal (Kanari and Millar 2004), and use experiments to achieve specific outcomes rather than test hypotheses (Schauble 1996). Though learners' ideas about the investigation context may lead them toward invalid experimental designs or inferences, students may also use ideas productively, such as by narrowing the range of testable values or eliminating implausible explanations. Tschirgi (1980) argued that children's tendency to use 'invalid' strategies when determining the ingredients needed to bake a good cake is reasonable, given real-life goals of reproducing positive results (good cakes) and eliminating negative ones (bad cakes). Koslowski (1996) also argued that using prior knowledge to generate and interpret evidence is a good strategy, particularly when understanding mechanisms informs the interpretation of outcomes. These studies indicate that learners' alternative strategies sometimes stem from efforts to refine their understanding of the situation, such as by narrowing the set of investigation questions or exploring the nature of the variables.

Other research shows the extent to which learners' prior understanding of the domain may affect their learning outcomes. Linn, Clement, and Pulos (1983) compared the students' reasoning in laboratory tasks and naturalistic tasks involving the effects of system variables on an outcome. The study found that part of the variance in performance on these tasks was associated with task content knowledge. Schauble (1996) examined experimentation by children and adults in two science domains. The study revealed that subjects who conducted valid experiments often reached invalid conclusions informed by their prior knowledge of the system, and that subjects' knowledge sometimes informed their experimentation strategies. These findings show how domain knowledge contributes to scientific reasoning. Knowledge of the domain can facilitate learning from experimentation but might also mislead.

The findings point to experimentation as an important way to extend learners' understanding of a domain, as well as to strengthen appreciation of the diverse methods scientists have devised to advance knowledge. Incorporating experimentation activities within inquiry investigations provides learners with opportunities to test their own ideas about the domain and use the outcomes of experimentation to generalise knowledge to new contexts.

Controlled experiments vs. informative experiments

Today researchers still conduct studies that minimise domain knowledge and focus on promoting mastery of the control-of-variables strategy (CVS) in science classrooms (Chen and Klahr 1999; Klahr and Nigam 2004). The studies present students with stand-alone experimentation tasks where the role of students' prior domain knowledge is negligible and students' understanding of the outcomes is inconsequential for subsequent tasks. These classroom tasks present experimentation to students as a procedure to be followed rather than a component of authentic science inquiry and treat the strategy itself, rather than insights about the context, as the relevant learning outcome. The implications of these studies for promoting valid experimentation in contexts where domain knowledge plays an important role are therefore unclear.

Characterising experiments as either controlled or uncontrolled may not capture the complexity of the insights students make during the course of experimentation. This chapter presents research that extends studies on students' mastery of CVS by examining a complex, realistic experimentation context. In this task, different controlled experiments for the same variable illustrate different types of variable relationships and not all controlled experiments are equally informative. In this way we make a distinction between *controlled* experiments and *informative* experiments.

Experimenting in realistic contexts requires learners to consider a wide range of ideas to design informative experiments. Learners need to integrate everyday ideas they have about the topic, formal knowledge about the science domain, and knowledge about strategies for experimentation in order to investigate complex questions. They need to focus their inquiry on the most salient issues. To make sensible decisions about experimental designs that test the multitude of ideas they hold, students need more than procedural guidance (such as domain general instruction of controlling variables). They need methods for sorting out their disciplinary knowledge and identifying compelling questions in order to learn how to conduct informative experiments. We draw from the knowledge integration perspective on learning (Linn and Eylon 2006) to suggest compelling ways that instructional designers can incorporate experimentation within rich, realistic, and relevant inquiry investigations.

Using the Knowledge Integration Pattern to Design Authentic Experimentation Activities

The knowledge integration (KI) perspective describes learning as occurring when students articulate their everyday ideas and intuitions then add new, normative ideas about science to their repertoire of ideas. Instruction then prompts students to bump these ideas up against one another, giving them opportunities to distinguish and evaluate ideas and resolve conflicts. These activities can help students monitor their own understanding so that they can identify and repair gaps in their knowledge. In this way, new knowledge is anchored to prior educational and personal experiences. The KI perspective informs the knowledge integration pattern, an approach to designing instruction that takes advantage of the variation in students' ideas to help learners achieve integrated understanding of science. The KI pattern guides students through four knowledge integration processes to help make the ideas in their repertoire cohere (Linn and Eylon 2006). Here we outline the four processes and discuss how they can help students integrate ideas from experiments.

Elicit ideas

First, instruction should *elicit ideas* that students have about the topic of study. Learners' initial ideas may reflect everyday experiences with the context of investigation and beliefs about the nature of science and experimentation as well as ideas students have from formal instruction. Eliciting ideas takes advantage of the variety of ideas that learners have about the investigation context and sets the stage for experiments to add new ideas that extend or conflict with students' prior ideas. Eliciting ideas near the beginning of an investigation can also motivate the need for experiments and encourage students to design informative experiments that provide relevant insights about the investigation.

The need to elicit students' ideas about the topic illustrates the value of connecting experiments to relevant contexts. Relevant socio–scientific issues

can tap the productive ideas students have about everyday science and provide students with a basis for making informed conjectures. Real world problems allow the investigation to center on compelling driving questions (Krajcik et al. 1999), which make the design and interpretation of experiments consequential to the investigation. Relevant investigation contexts also reflect authentic practice of science inquiry and illustrate that experiments are a means to answering scientific questions rather than ends in themselves.

Add ideas

Next, instruction should *add normative ideas* to students' repertoires. Typical experimentation activities add ideas by illustrating monotonic (and often linear) relationships between system variables and outcomes. These relationships often illustrate key concepts in the scientific domain, such as how plants respond to sunlight or how frictional force relates to the mass of an object. These ideas are just a subset of the ideas that experiments can add for students.

In realistic experimentation contexts, aspects of experimentation may be less straightforward than in typical tasks. For instance, variables may exhibit non-linear or piecewise relationships to outcomes in situations where threshold values govern outcomes, or variables may interact. Experimentation can thus add ideas about the multitude of ways variables can vary with outcomes. Furthermore, a virtual experimentation environment may take advantage of scientific representations such as graphs or molecular models to add ideas about scientific representations.

Complex experimentation tasks may require scaffolding instruction in order for students to be successful. Inquiry investigations can add the ideas about the domain students need in order to design and interpret informative experiments. This approach makes scientific knowledge consequential for the experimentation task and motivates the need for new ideas.

Distinguish ideas

Third, instruction should encourage learners to *distinguish their ideas*. Experimentation by its very nature concerns distinguishing outcomes for one set of conditions from another – this is the main purpose of experiments. In typical experimentation tasks, students distinguish between the effects of different values of the same variable, illustrating covariation relationships. Instruction may also prompt students to distinguish observed outcomes from their expectations and to explain discrepancies. In a sense, distinctions comprise the essence of experimentation as a method of scientific inquiry.

Guiding students toward conducting valid, controlled experiments does not ensure that students will adequately distinguish ideas. Our studies suggest that even students who conduct valid controlled comparisons may not attend to the distinctions that serve as evidence in support of their views or that lead to relevant insights about the investigation. In a vignette later in this chapter, we illustrate how students' attention to the logistics of isolating variables can preclude them from considering the nature of the variables.

Designing tasks around realistic scientific contexts provides students with more opportunities to distinguish key ideas. For instance, important considerations in many variable systems are the magnitude and pattern of each variable's effect on outcomes. Inquiry questions that highlight the unique nature of each variable can prompt students to distinguish the variables from each other using these criteria. Driving inquiry questions that address the overall investigation goals rather than specific system variables can force students to connect variables to investigation goals for themselves. This activity can help students further distinguish the nature of the individual variables.

Sort out and refine ideas

Finally, instruction must allow students to *sort out and refine their ideas* in order to identify and repair gaps in their own understanding. Typical experimentation tasks may ask students to summarise their experimental results but neglect to provide opportunities to apply or generalise the findings. Summary may not compel students to evaluate the knowledge they build from conducting experiments, possibly leaving gaps in understanding. Inquiry instruction should make the findings from experiments consequential so that students recognise when their knowledge is insufficient to address the inquiry goals. Students can then revisit their experiments or conduct additional trials to strengthen connections among their ideas.

Realistic investigation contexts allow knowledge students gain from experiments to be consequential. Consequential tasks require students to bring multiple sources of evidence together, such as domain knowledge, observations and outcomes from experiments, research from the World Wide Web, ideas from peers, and everyday conceptions of science. These activities can take many forms, such as constructing an argument (as in a debate or persuasive essay), designing an artifact, or critiquing the arguments, designs and viewpoints of others.

In summary, realistic experimentation activities have the potential to help students' link scientific ideas to their everyday ideas about science. Realistic experimentation tasks embedded within inquiry investigations provide an alternative to typical laboratory experiments in their emphasis on the nature and purpose of experimentation and the role of experimentation in addressing relevant, real-world problems.

Investigating a realistic problem: *Airbags: Too Fast, Too Furious?*

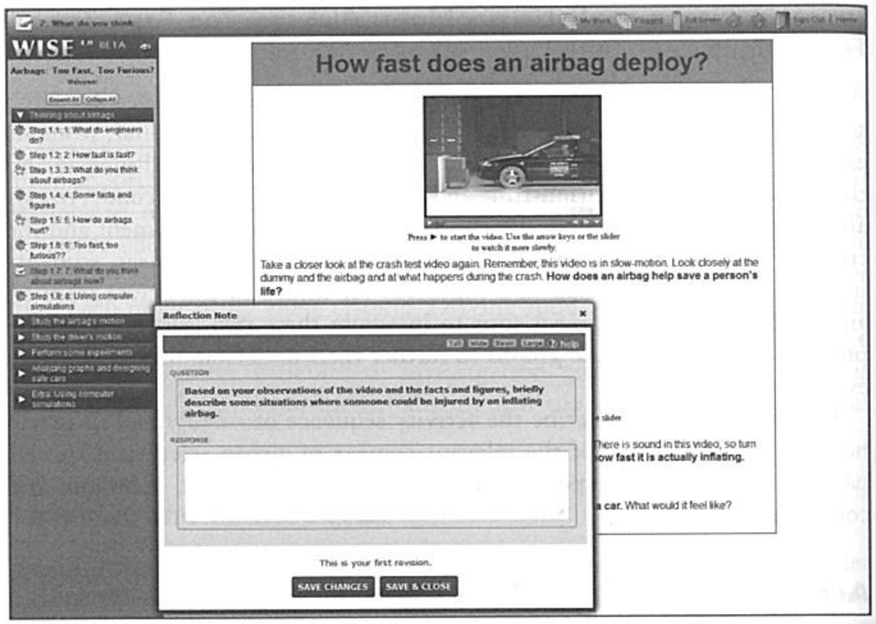
Airbags is a week-long computer-based inquiry module designed for high school physics classes. *Airbags* has two primary learning goals. First, students examine the relationship between the nature of one-dimensional motion and the characteristics of position-time and velocity-time graphs. Second, *Airbags* aims to help students understand the dynamics of airbag deployment and the risks for injury from an airbag in a head-on collision. In *Airbags*, students investigate factors that lead to a high risk for injury to the driver from an airbag. The design of *Airbags* aims to integrate these two learning goals by prompting students to use graphs to further their understanding of collision events.

In this section, we describe the activity sequence of *Airbags* and illustrate how it takes advantage of the relevant context of airbag safety and the KI pattern to make the experimentation activity meaningful, relevant, and consequential.

Activity 1: Orient and Elicit Ideas

Activity 1 introduces students to the investigation context, elicits their ideas about how airbags work and why they might present dangers in certain circumstances. A screenshot of the first activity of *Airbags* appears in Figure 3.1. The activity presents students with different types of evidence, such as a slow motion video of a head-on crash test, a full-speed video of an airbag deploying, and fatality statistics from accidents involving airbags. Students articulate their initial ideas in response to prompts concerning how airbags are designed to work, why they must deploy at such high speed, and the conditions in which they might be dangerous. The activity encourages students to view the crash test video multiple times to familiarise them with the sequence of events that occur during a head-on collision. The prompts guide students toward developing the primary criterion for determining whether the driver was injured by the airbag – encountering an airbag that has not finished inflating. The subsequent activities build on these ideas by introducing the motion characteristics as variables and the safety of the driver as the outcome in experimental trials.

The early steps in *Airbags* were successful in motivating the topic for study. We designed *Airbags* for students at or near legal driving age in the United States, making automobile safety a particularly relevant topic for many students. Furthermore, the motion and forces that students experience as either drivers or passengers in cars from day to day provide students with a kinesthetic understanding that can be extended to this investigation. The dramatic videos depicting crash tests and the real-time airbag deployment video contributed to capturing students' interest, as did



How fast does an airbag deploy?

Press ▶ to start the video. Use the arrow keys or the slider to watch it more slowly.

Take a closer look at the crash test video again. Remember, this video is in slow-motion. Look closely at the dummy and the airbag and at what happens during the crash. **How does an airbag help save a person's life?**

Based on your observations of the video and the facts and figures, briefly describe some situations where someone could be injured by an inflating airbag.

This is your first revision.

Figure 3.1 Screenshot of an evidence step and an embedded prompt in Activity 1 of *Airbags*.

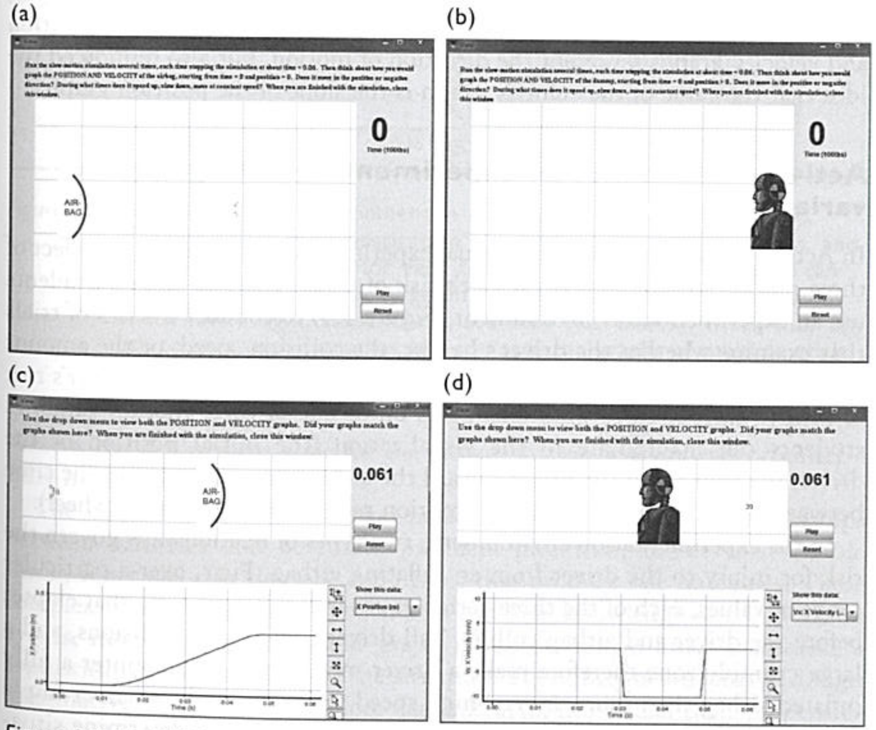
examples of visualizations that professional engineers use to study the safety of automobiles. The impact of these videos was likely enhanced for students who had driving experience. Many students noted that they thought about the *Airbags* module when they drove their car during the week in which they used the module in their classrooms. The topic of car safety thus resonated with these students at a personal level.

The value of the compelling investigation context goes beyond capturing students' interest. The videos and fatality statistics prompted students to consider the speed of the airbag deployment as a trade-off between protecting and injuring the driver, depending on the conditions of the collision. Class discussions helped engage students in debating the design features of cars and airbags in light of this trade-off. The limited information students had to debate this issue at the beginning helped make the use of physics to analyse the situation consequential.

An early embedded prompt asked students to interpret the fatality statistics, which showed women to be at greater risk for death from impact with airbags. In our most recent study with *Airbags*, 60% percent of students' responses attributed the gender difference to irrelevant factors such as driving skill or inattention (due to applying make-up, for example). Class discussions revealed many students' awareness about greater insurance premiums for men compared to women and that this evidence conflicted with their initial interpretations. This discrepancy provided motivation for students to design experiments that would generate evidence for alternative explanations. Responses to assessments near the end of the module showed students greatly improved their understanding of the gender disparity. We discuss these improvements below.

Activities 2 and 3: Add and distinguish ideas about motion and graphs

Activities 2 and 3 focus on helping students add and distinguish the ideas about motion and graphs that are needed to conduct and interpret their informative experiments. These activities add ideas about kinematics that help students understand the nuances of motion of the airbag and the driver during the collision and how graphs represent this motion. *Airbags* prompts students to rewatch the crash test video while focusing on the motion of the airbag (for Activity 2) or the driver (for Activity 3). Students observe a simple animation of this motion (Figure 3.2 (a) and (b)), use a drawing tool



Use the drop down menu to view both the POSITION and VELOCITY graphs. Did your graphs match the graphs shown here? When you are finished with the simulation, close this window.

Use the drop down menu to view both the POSITION and VELOCITY graphs. Did your graphs match the graphs shown here? When you are finished with the simulation, close this window.

Figure 3.2 Scaffolding visualizations in Activities 2 and 3 of *Airbags*. Students observe an animation of motion [(a) and (b)], predict the appearance of graphs, then observe computer-generated position or velocity graphs simultaneously with the motion [(c) and (d)].

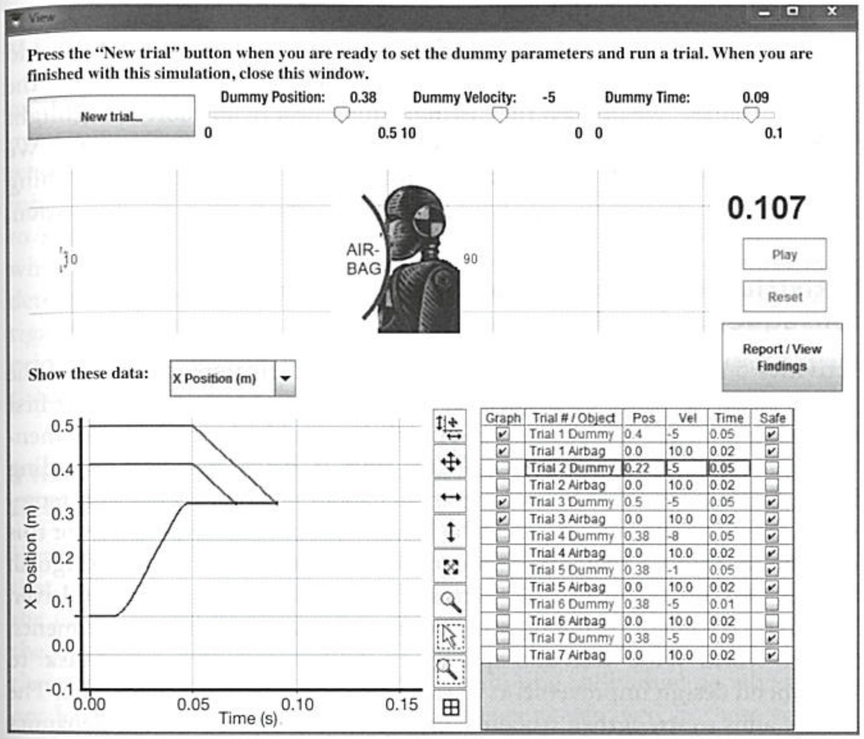
to sketch position and velocity graphs of the observed motion, then observe the animation concurrently with dynamically generated position and velocity graphs (Figure 3.2 (c) and (d)). The visualizations add ideas about the nature of the motion of the airbag and the driver, and how different features of the graphs represent different characteristics of motion.

After using the visualizations, *Airbags* prompts students to distinguish between the computer-generated graph and their own graph, among different parts of the graph from each other, and between graphs of motion in opposite directions. These prompts call students' attention to the difference between their initial ideas and new normative ideas about graphs and highlight distinctions among positive, negative, and zero velocity and acceleration. We observed a common interaction that students had with their teachers during the third activity as they sketched their prediction of the position and velocity graphs of the driver's motion. After having struggled with the graphs of the airbag's motion in the previous activity, many students drew accurate graphs of the driver's motion that neglected only to represent the correct direction of motion (opposite to that of the airbag). When these students observed the computer-generated graphs (which were inverted versions of their own graph), the difference between the two graphs not only highlighted how both position and velocity graphs represent the direction of motion, but also reinforced the idea that the value of the velocity graph is the slope of the position graph.

Activity 4: Conduct an experiment to distinguish the variables

In Activity 4, students conduct virtual experiments to investigate the effect of three motion variables on the driver's risk of injury from an airbag. Students use an experimentation environment (Figure 3.3) to conduct a series of trials that examine whether the driver's height, the collision speed, or the amount that the car can crumple on impact has the greatest effect on the driver's risk of injury. Each of these questions maps on to one of three motion variables students can manipulate in the visualization (the initial position of the driver, the velocity of the driver toward the airbag after impact, and the time between impact and driver's initial motion relative to the steering wheel).

In the experimentation environment, two types of relationships govern the risk for injury to the driver from an inflating airbag. First, over a particular range of values, each of the three variables covaries with the time that elapses before the driver and airbag collide. Tall drivers, low speed collisions, and a large crumple zone therefore make a driver more likely to encounter a fully inflated airbag than short drivers, high speed collisions, and a small crumple zone. Second, two threshold values (for position and time) determine situations where the likelihood of injury is invariant: (1) short drivers who sit within an airbag's zone of deployment will *never* encounter a fully inflated airbag, and (2) for sufficiently tall drivers, if the duration of the crumple zone



Press the "New trial" button when you are ready to set the dummy parameters and run a trial. When you are finished with this simulation, close this window.

Dummy Position: 0.38

Dummy Velocity: -5

Dummy Time: 0.09

Graph	Trial # / Object	Pos	Vel	Time	Safe
☑	Trial 1 Dummy	0.4	-5	0.05	☑
☑	Trial 1 Airbag	0.0	10.0	0.02	☑
☐	Trial 2 Dummy	0.22	-5	0.05	☐
☐	Trial 2 Airbag	0.0	10.0	0.02	☐
☑	Trial 3 Dummy	0.5	-5	0.05	☑
☑	Trial 3 Airbag	0.0	10.0	0.02	☑
☐	Trial 4 Dummy	0.38	-8	0.05	☑
☐	Trial 4 Airbag	0.0	10.0	0.02	☑
☐	Trial 5 Dummy	0.38	-1	0.05	☑
☐	Trial 5 Airbag	0.0	10.0	0.02	☑
☐	Trial 6 Dummy	0.38	-5	0.01	☐
☐	Trial 6 Airbag	0.0	10.0	0.02	☐
☐	Trial 7 Dummy	0.38	-5	0.09	☑
☐	Trial 7 Airbag	0.0	10.0	0.02	☑

Figure 3.3 Experimentation environment in Activity 4 of *Airbags*. At the top, students select and investigation question, specify variable values, and observe the animation for each trial. In the lower left, students can view a position or velocity graph of the airbag's and driver's motion. In the lower right, students can see their trial history, which they can use to sort trial outcomes and compare the graphs of multiple trials.

exceeds the deployment time for the airbag, drivers will *always* encounter a fully inflated airbag.

The combination of covariation-based and threshold-based relationships between variables and outcomes produces piecewise, rather than simple linear, functions that describe conditions that produce safe outcomes. These complex relationships force students to combine knowledge of the collision events, motion parameters, and graph interpretation in order to achieve a sophisticated understanding of the situation. The ability of students to design informative experiments therefore depends upon more than their propensity to control variables in an arbitrary manner.

The inquiry question of determining the variable that has the greatest effect on the outcome is a distinguishing task. We also studied versions of *Airbags* that presented students with a more typical task of examining the effect of the individual variables on the outcomes. We found that in response to the typical task, many students failed to reach insights that would arise from identifying distinctive features of the variables, particularly the threshold values. We devised the distinguishing task in an effort to highlight the roles of the distance and time thresholds on the collision outcomes. We follow this section with three vignettes that illustrate how the distinguishing task helped students reach sophisticated insights about the airbags situation.

Activities 5 and 6: Sort and refine ideas with consequential tasks

Activities 5 and 6 aim to help students evaluate their understanding of the airbags situation using consequential tasks. Activity 5 achieves this by first presenting students with examples of collision graphs from the experimentation environment as hypothetical data from a 'black box' data recording device. Students must construct arguments about whether each graph represents a safe or unsafe outcome and which variable was most responsible for this outcome. Activity 5 then asks students to construct graphs that distinguish between two collision scenarios, such as those involving a tall or a short driver. In Activity 6 students bring together evidence from the module, experiments, and the World Wide Web and apply it to the first step of a design task: to recommend design improvements to cars and airbags to make them safer. The activity aims to strengthen students' understanding of the collision dynamics by applying their understanding of factors that lead to injuries from airbags. Arguments and design tasks require students to determine whether their current state of understanding is sufficient to address the broad goals of the inquiry investigations. If their level of understanding proves to be inadequate to construct a cogent argument or to inform the initial design effort, students may be compelled to revisit previous evidence to refine their understanding.

We observed students reaching insights from discussions with their working partner in efforts to reach consensus on arguments and design considerations. These discussions were likely enhanced at least in part by the design of the prompts. Rather than simply asking students to explain an observation or phenomenon, the prompts provided students with just two or three choices and asked them to defend just one of the views. For instance, some prompts asked students to explain why a graph illustrated a safe or an unsafe outcome. Other prompts asked students to choose the collision factor that was most responsible for the outcome. Requiring each dyad to take a particular position helped students recognise when they were in disagreement with their partner and required them to achieve consensus. Students often asked us to resolve disagreements between group members as they attempted to generate a unified response to these prompts. In these situations, we would ask each student to summarise their own point of view and engage them in a mini-debate. Sometimes we would instruct students to revisit evidence, such as the videos or their experimental results, to better support their views.

As we noted earlier, 60% of students attributed increased risk for women to irrelevant factors. In a similar argumentation prompt after the experimentation activity, *Airbags* presents a scenario that asks students to explain whether a short, stocky man or tall, thin woman is at greater risk for an airbag injury. On this item, the percentage of students who use irrelevant evidence to support their view fell to just 11%, while the percentage of students who correctly identified the driver's distance from the steering wheel as the determining factor in this scenario was 73%. The ability of the *Airbags* investigation as a whole to shift students' views from uninformed to those based on evidence illustrates the importance of giving students opportunities to refine their understanding of the everyday application of science.

Three Vignettes: Using Experiments to Highlight Key Distinctions

Here we present three vignettes that illustrate how an experimentation task that emphasises distinctions among the variables helped students consider the nature of the variables in the Airbags situation. These vignettes focus on the ways that the distinguishing inquiry task helped students reach insights that a typical experimentation task of examining individual variables might not have allowed them to make. All students names used in these vignettes are pseudonyms.

Vignette 1: 'Let's go to the next question.'

We first discuss Brett and Eric, who studied the version of *Airbags* that presented the typical task of examining the variables individually. Brett and Eric were enrolled in a science and mathematics program that had high standards for admission and that served the strongest students in their metropolitan area. Students in this program are concurrently enrolled in calculus and nearly always attend four-year colleges. Brett and Eric had the following exchange while conducting a controlled comparison for the position variable:

E: …Short or tall. And now we have to move the guy back, 'cause he's taller. So we gotta keep everything except position. So move him back some. Like right there.

B: He's going to be safe, obviously.

E: He might not, let's just check. [They run a new trial.] Yeah. So mark that as safe. OK, put the graphs for the previous two. [They compare the graphs of the two trials]

B: They're both safe.

E: Yeah. So let's go to the next question.

This exchange illustrates two ways that their controlled test, though 'valid' in the strict sense of varying only one of the variables, failed to be especially informative. First, because the first of these trials produced a 'safe' outcome, Brett knew in advance that the outcome of the subsequent trial, which they conducted with the driver at a greater distance from the airbag, would also be 'safe.' However, rather than choosing a set of values that would provide them with new insights, they simply completed the test they had initially planned. Second, because both of these trials produced 'safe' outcomes, they failed to provide any evidence for their ultimate conclusion – that short drivers are at greater risk for injury.

This example illustrates why controlled experiments are not necessarily informative. Further tests aiming to illustrate conditions that led to an 'unsafe' outcome might have better informed their understanding and possibly highlighted the role of the distance threshold in determining collision outcomes. However, their variable choices and the brevity of their discussion about the results suggest they are focused more on the perceived requirement of isolating variables than on gaining insight about the situation.

A subsequent conversation during their next set of controlled trials sheds more light on their experimentation approach:

E: ...since we're doing, like, experiments, we can only change one of them, we can't change multiple ones.
B: Yeah.
E: 'Cause like in real life, there would be a combination of all three.

Eric appears to believe he is prohibited from doing anything other than isolating individual variables, even though at no point does *Airbags* instruct students on how to design experiments. Furthermore, the distinction he makes between their task and 'real life' indicates he believed these other strategies would be permissible in other contexts. Though Eric did not elaborate on what he meant by 'a combination of all three', his comments suggest he views the task of isolating variables as being a requirement of classroom science, and that in an authentic setting the investigation would require a more complex approach.

Brett and Eric provide an interesting example of students who are able to articulate the complexity of the problem in front of them but appear consciously to ignore this complexity. Their decision raises issues about the conflicting goals of classroom science and authentic inquiry. The contrived nature of Brett's and Eric's investigation approach suggests that the typical task of examining individual variables failed to jar them into a mindset that prioritised deepening their knowledge about the investigation over doing what was expected of them as high-achieving science students. Brett and Eric might have benefited from engaging in the distinguishing task, which they might have perceived as more challenging, authentic, and realistic.

Vignette 2: 'We're kind of figuring it out as we're looking at this.'

Joann and Linda were enrolled in the same selective science and math program as Brett and Eric. Joann and Linda studied the version of *Airbags* that presented the distinguishing task of determining the variable with the greatest effect on the collision outcome. Like Brett and Eric (and many other students), they began their investigation of the variables by planning an approach that would isolate each variable at three distinct values of the other variables:

L: I don't know. Maybe we just test ummm, like, test the position at, like, three different points. That's just so – that's just so many tests, never mind....

At this point they use their first three trials to isolate the position variable and test its full range but are soon discouraged by the sheer length of their proposed approach (27 trials in all). After choosing intermediate values for their fourth trial and discussing the outcome, their discussion about the 'effect' of the car crumpling empowers them to abandon their default isolation of variables strategy:

J: See we keep – we kept all that the same, but the farther away it was, the safer. Keeping the velocity and time on track. Because I would imagine let's say you had – it was closer, and it goes right there, and you had the dummy time at like 1 full second, that would give it more time to inflate. So then the dummy wouldn't start moving until 7.5.
L: Right, OK.
J: So it's an extra half – time ... or whatever ... And if you decrease the velocity, they can move slower, which I'm assuming is a slow crash, like slow impact crash.
L: OK.
J: Then it all falls back to what we said originally, the crash, the speed of the crash dictates if position and dummy time, you know, the crumpling of the car would have an effect.
L: Yeah. I don't understand why we have to do different tests for each three different sections [investigation questions]. You know? You click on them and be like whatever trials for this, kind of. 'Cause it looks like we're kind of figuring it out as we're looking at this.

This excerpt sheds light on their rationale for changing their approach. Joann summarises the results of their initial controlled trials using the typical covariation approach ('the farther away it was, the safer'). However, their view of the inquiry task appeared to change when they recognised that a simple covariation-based explanation was insufficient to address their inquiry questions. Their discussion turned to the trade-offs between variables (e.g. reducing the position but increasing the time) and their pre-experimentation hypothesis (that the speed 'dictates' the effects of the other variables). At this point they began conducting trials in a more spontaneous way in an effort simply to 'figure it out.'

The stark differences between these first two vignettes illustrate how asking students to distinguish the variables might have changed their entire conceptions of the task. For Brett and Eric, the typical isolation of variables task appeared to provoke a 'schoolish' response. They viewed the task as a simple covariation problem (a common class of problem in school science), and as a result they prioritised a valid control of variables design over gaining insight. In the process, they sequestered their classroom inquiry investigation from the real life practice of authentic science. Their analysis never went beyond a superficial characterization of the variables. The investigation questions in the typical task did not challenge Brett and Eric to deepen their understanding of the situation.

In contrast, Joann's and Linda's task of distinguishing the variables ultimately led them to incorporate a wider range of strategies to elucidate variation patterns. They conducted trials with the intention of understanding the relationships between variables and outcomes and the mechanisms that governed these relationships. Their questions encouraged them to consider the nature of the variables and to determine the unique contributions of each variable toward the outcome. This approach reflects an authentic, rather than a 'schoolish', view of the inquiry task.

Vignette 3: 'Why are they the same?'

Christine and David were enrolled in a physics class (at a different school from the students in the previous vignettes) comprised of students having wide-ranging science and mathematics ability. As with Joann and Linda, *Airbags* presented Christine and David with the distinguishing task. In this vignette, Christine and David conduct a controlled comparison for the velocity variable. Because they have set the position variable to a value within the airbag's deployment range, they achieve identical outcomes where the airbag injures the driver. As they compare the graphs from these identical outcomes, they have the following exchange:

D: Um, wait, go back to the other graph? Isn't that kind of like the same?

C: Yeah. Yeah. So...

D: Mm.

C: Why are they the same?

D: All right. Faster speed equals less safe.

Christine and David have distinctly different responses to the outcome of Trial 5. Christine appears to be interested in what causes the results. David, however, seeks evidence for covariation between speed and risk for injury, despite observing two identical outcomes. His statement 'faster speed equals less safe,' while it reflects the conventional wisdom that drivers are more at risk for injury in high speed collisions, completely ignores the evidence they generated in their experiment. Their next trial breaks David's grasp on the conventional wisdom:

C: ... It still looks the same!

D: Well that's like the airbag hitting *him* [verbal emphasis]. So he's like, driving driving driving driving driving, and the airbag's coming, psh, and it's hitting him. And then it will be like stopped, and he didn't go into it, it just kind of blew into his face, so that means that he'd be...not good.

C: Yeah, but I mean like, it still looks the same as if it was going slower. Still the same effect, the position doesn't change so that person stays the same height obviously.

D: I think I kind of get it, like. Like, um, our hypothesis was, you know, for this, the height made a difference, like the taller you are, then the safer you're going to be, and the smaller you are, the not safer you're going to be. And we thought it was really the speed that was going to affect it, but, whether you're going slower or faster, the airbag coming out and hitting you [gestures hand toward face], you know –

C: The same.

D: It's gonna be the same.

C: Oh OK, I get you.

D: So really, the speed doesn't affect it.... right now, it's more the height.

This vignette illustrates a couple of important ways that the distinguishing task and the realistic nature of the *Airbags* investigation led Christine and David to reach insights they likely would not have reached using a more typical experimentation task. First, David's detailed narrative accounts of the dynamics of the interaction between airbag and driver illustrate the degree to which their everyday understanding of the situation informed their interpretation of the experiments. Without this realistic context, they would have great difficulty making sense of the identical outcomes they observed for their controlled comparison. The *Airbags* context not only gave them information they could use to explain the results, but also gave their conclusions personal meaning.

Second, Christine and David were able to reach an important insight concerning the relative effects of the driver's height and collision speed in determining the safety of the driver. Distinguishing the variables led them to incorporate the unique nature of each variable into their explanation of the results. Throughout their experimentation sequence, David attempted to characterise variable relationships using statements of the form 'more x equals more y.' This tendency toward interpreting all outcomes in this way likely stemmed at least in part from school science's emphasis on covariation relationships. The complex nature of the variable relationships in the *Airbags* task produced an unexpected outcome, forcing them to reconcile their 'schoolish' expectations of covariation with their conflicting observations. Their insight reflects their efforts to make sense of the results in the context of everyday life rather than characterise them according to rules that did not apply to the situation.

Implications for Inquiry Instruction

The knowledge integration framework suggests ways for instruction to help students develop authentic views of experimentation within inquiry investigations. Centering investigations on realistic, relevant contexts encourages students to take advantage of their knowledge in designing experiments and in reasoning about their findings. This way, students can design experiments that test their ideas rather than merely follow a recipe that may not connect to their prior conceptions or relevant everyday ideas.

Our findings illustrate that some students have developed a formulaic approach to controlling variables, possibly from prior instruction. These students appear to miss subtleties in the investigative context and lack a propensity to make sense of their investigations. School science may condition students to focus on valid procedures at the expense of understanding the scientific implications of their experiments. As mentioned at the onset, this might stem from standards that endorse a specific view of experimentation and that equate valid experimentation with controlled tests. Another reason may be that students lack opportunities during typical instruction to conduct experiments in meaningful contexts.

Our studies illustrate a major challenge of inquiry instruction: the need for students to take on the role of scientific investigator and (to some extent) let go of their role as a science student. As Brett and Eric demonstrate in our first vignette, the students' classroom goals (such as earning a good grade or minimising effort) can interfere with making meaningful insights about realistic investigations. Designers of inquiry instruction should be mindful of ways in which students' beliefs about classroom science can preclude authentic interpretations of inquiry investigations. The success of students engaged with the distinguishing task of *Airbags* illustrates the substantial effect that subtle changes in framing of inquiry tasks can have on students' insights. In *Airbags*, presenting students with a set of uncommon investigation questions appeared to jar some students out of their roles as science students and encourage them to make more authentic inquiry choices.

The distinguishing task was not equally effective for all students who studied *Airbags*. For students who found the distinguishing task too difficult, a more direct method of scaffolding might have been more helpful. For example, we might have explicitly asked students to identify values of position, velocity, and time values that were particularly important to determining the outcomes, then prompted them to distinguish the variables on this basis. Using logging technologies currently available in WISE and other learning environments, this direct guidance might be provided if students conduct experiments in a way that does not provide evidence for these distinctions between the variables. Identifying the best forms of guidance for experimentation, as well as employing guidance that is adaptive to the nature of students' inquiry moves, are important avenues for future research on technology-enhanced inquiry instruction.

Finally, our studies emphasise the importance of conducting research on inquiry in classroom contexts. Uncovering the ways students' beliefs about classroom science affect their interpretation of inquiry tasks is not possible with laboratory studies. We illustrate that the extent to which students are conditioned to think about scientific investigations and their goals as science students can profoundly influence learning outcomes from inquiry investigations, even those about relevant everyday contexts. Research should continue to examine how students' beliefs about classroom science can affect the effectiveness of inquiry instruction. We hope that further research on inquiry learning will continue to challenge the norms of typical science instruction and bridge the gap that exists between classroom and professional views of science. These research efforts have the potential to benefit students not only within the classroom, but also as lifelong learners.

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Chapter 4

Designing orchestration for inquiry learning

Mike Sharples and Stamatina Anastopoulou

> For so long teaching has been regarded as a human task that it is novel to suggest that a machine should take over the role of contact with the students, and leave a teacher to do the planning and preparation of the lesson. But it does seem to work, and in a world that is short of teachers there is every reason to develop it as far as possible.
>
> (Dodd, Sime and Kay 1968).

Background

From the earliest years of computer-based instruction there has been an ambition for computers to act as tutors, delivering personalised teaching to pupils while human teachers are promoted to learning managers (Dodd, Sime and Kay 1968). For many reasons the vision has never become a reality. Designing and implementing adaptive computer-based tutoring is a skilled and time-consuming task, one that requires the software developers to have a deep knowledge of the domain, the differences in knowledge and misconceptions of learners, and the structure and progress of the lessons, in a form that can be implemented as a tutorial computer programme. By contrast, most teachers are rather good at maintaining personal contact with students, guiding each of them through programmes of study suited to their needs and abilities. The irony is that rather than reducing the work of teachers, modern technology-mediated classrooms are requiring them to take on the dual roles of educator and learning manager.

As learning becomes more mechanised, through lesson plans, web-based resources, and re-usable learning objects, so teachers become conductors of an orchestra of students equipped with their learning instruments. The term 'orchestration' has been used by educational researchers to refer to the design and classroom management of a sequence of activities for individuals and groups to enable effective learning (e.g. Forman and Ansell 2002), and has been adopted by researchers in computer supported collaborative work to describe the management by a teacher, in real time, of a class of learners supported by interactive technology (Dillenburg and Jermann 2007;