Tensions and Tradeoffs in a "Design for Science" Classroom: The "Forces in Balloon" Lecture

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Abstract: "Design for science" curricula employ engineering-type design challenges as means for students to learn science concepts as well as skills in science and design. Teaching science in the context of engineering design, however, is not straightforward; it creates certain tensions and requires tradeoffs. This paper represents part of a larger study that examines and describes tensions and tradeoffs in a "design for science" classroom, Learning by Design™. We examine tensions in a lecture on *forces* in which the teacher finds herself challenged to build representational bridges between students' designed artifacts and abstract science concepts. Constrained by time and difficulty of the concepts, the teacher chooses a tradeoff that uses a lecture to provide students a model for the science underlying their designs. Our examination reveals the teacher's struggle with representation, the requirement that she engage in modeling, and the importance of in-depth pedagogical content knowledge to successful design-based science instruction.

Introduction

Many curriculum developers have been drawn to engineering design activities as a means of providing students real-world contexts for science concepts (e.g., Fortus, Dershimer, Krajcik, Marx, & Mamlok-Naaman, 2002; Kolodner et al., 2003; Seiler, Tobin, & Sokolic, 2001). In these settings, engineering design is typically used to scaffold science learning, as well as to support general education goals such as decision-making and working in teams. However, engineering design has significant distinctions in its goals, activities, and knowledge that make it not a simple "plug-and-play" context for science learning (Leonard, 2004); it gives rise to tensions and requires tradeoffs in the science classroom. In light of educators' and education researchers' interest in design-based contexts for science, it is important to further our understanding of what happens in such classrooms, to enable us to more effectively capitalize on design for science learning.

This paper presents a piece of analysis from a larger study (overview provided in Leonard, 2005) that is investigating tensions in an enacted "design for science" (DS) curriculum, Learning By Design™ (LBD) (Kolodner et al., 2003). The setting is Ms. Harding's (a pseudonym) middle-school classroom where students were challenged to design and build a balloon-powered miniature car to go as straight and far as possible over level terrain. The study draws on activity theory (Engeström, 1999; Leont'ev, 1978, 1981) and discourse analysis (Gee, 1999) in an ethnographic approach that examines practices, goals and other factors that mediate activities in the enacted curriculum. Two concepts are of particular interest to this analysis: what activity theorists have termed *tensions* occurring at places in the activity system where some of its elements are not well-aligned, and *tradeoffs* made when deciding between several possible solutions to a design problem.

The LBD classroom under study was originally videotaped for production of a teaching case of an innovative curriculum to be used in a pre-service teacher education course (Derry, Seymour, Steinkuehler, Lee, & Siegel, 2004). However, video is especially amenable to secondary analysis and this classroom video later became a "remnant case" (Hall, 2003) and the focus of further study. The present analysis focuses on an approximately 4½ minute, videotaped episode from a lecture in which the teacher explains how forces-in-pairs (i.e., Newton's Third Law) act to propel students' balloon cars – dubbed the "forces in balloon" explanation. This episode came to the fore when the educational researchers editing the video for its original purpose became caught up in trying to understand the "forces in balloon" explanation themselves. It was subsequently made the subject of analysis by a science education professor and physicist, by the teacher in a video-stimulated retrospective interview, and by our lab's research group in an interaction analysis. Our analysis revealed that although scientific *modeling* was not explicitly addressed in the curriculum or discussed by the teacher, developing and communicating an explanatory model was exactly what she was challenged to do in her lecture. Indeed, as in science and mathematics, modeling is inherent to working within engineering design. The teacher's explanation further required her to draw on a base of knowledge and skills closely related to modeling, that of *pedagogical content knowledge* (PCK), which includes a collection of analogies, explanations, and representational systems that can be used to help students acquire conceptual understanding (Shulman, 1986, 1987). The teacher and some of the curriculum developers identified the lecture as critical in "getting to the science" (Ms. Harding, Reflection, 11/30/01) of balloon car motion. Although not discussed here, the larger study goes on to consider how students' own conceptual models of balloon car motion are revealed in their discourse and how expression of their models may have changed as a result of the "forces in balloon" explanation.

The lecture episode illustrates important issues related to teaching science in the context of a design activity. Specifically, the teacher is challenged to build representational bridges between the design artifacts created by students and the abstract science concepts that are the goals of instruction. Faced with the difficulty of the concepts and under the constraint of time, the teacher elects to provide an explanation to the students. In her words,

> The balloon engine, as an entity, is complicated for kids; it's complicated for adults. And to have them understand exactly where there are forces, in something that is very abstract, even though it's sitting in front of them – we think we've given them a tool, but it's still very abstract to them. They need help with that. That's what they need the teacher for. (Ms. Harding, Reflection, 11/30/01).

In examining this example of explanation in inquiry instruction, we uncovered and illuminated the nature of a struggle with representation that underscores the role and importance of the teacher's science understanding as well her ability to flexibly represent that understanding and to make spontaneous decisions about pedagogically-effective representations.

The "forces in balloon" explanation

Part of what attracts researchers to video is its richness of detail, but reporting a video analysis on the printed page forfeits much of that richness. Seeking to preserve some of video's affordances, we chose to include here as detailed an account of the "forces in balloon" explanation as possible within our constraints of medium and space.

The classroom under study is Ms. Harding's eighth-grade, talented and gifted physical science class in a suburban area of a large Southern city. The curriculum began with a three-week introductory unit intended to "launch" them into the practices of LBD. Three "design challenges" followed the introductory unit, each lasting an average of two weeks; the balloon-car was the second of the three. The balloon-car activity focused on iterative experiment and design by small groups of students but also included whole-class lecture, discussion, and student presentations. By the time of the forces-in-pairs lecture, students had progressed through a first round of experiments and presentations on variables thought to affect their cars' performance. Ms. Harding began the lecture with several demonstrations to show that forces operate in pairs, "this idea, that when two objects interact they each experience a force that's equal in size and opposite in direction" (Ms. Harding, Interview, 08/09/05). The lecture ultimately arrived at the point of examining how forces in pairs propelled the students' balloon cars. (All quotes following in this section come from Ms. Harding, Lecture, 11/30/01 unless otherwise attributed.)

The teacher started her "forces in balloon" explanation by drawing a balloon car on the board with arrows representing a pair of forces: "air pushing balloon" and "balloon pushes air" (Figure 1a). When her questions of students did not return the understanding she sought, Ms. Harding took a new approach; "Okay, we need to look at the anatomy of this a little bit ... more carefully." She demarcated a section of the balloon opposite the straw using two lines (Figure 1b) and pointed out,

> Right here something interesting happens. This is the part of the balloon that if this were closed *(draws a line closing off balloon at straw)*, right, this opposite part, there would be some resistance on the other side *(points to balloon opposite the straw)*, right? ... But when this gets opened *(erases line at straw)*, the air can get out. So this part of the balloon *(draws over balloon opposite the straw)* doesn't have a resistance on the other side. So this air that's pushing here *(points to balloon opposite the straw)* is still here.

Again Ms. Harding determined that students didn't understand the concept, so she took another tact; "Okay, let's look at this a little bit different, I see confused looks." Under the balloon car drawing, she drew two arcs representing opposite sides of the balloon (Figure 1c). She began,

> This is all air in here *(writes "AIR" between arcs)*, and these lines represent your balloon *(traces over arcs)*. The air's pushing here and here *(draws arrows pointing out to each arc, a1 & a2)*. The balloon is pushing back.... The balloon is pushing this direction *(draws arrow pointing in from each arc: b1 & b2)*.

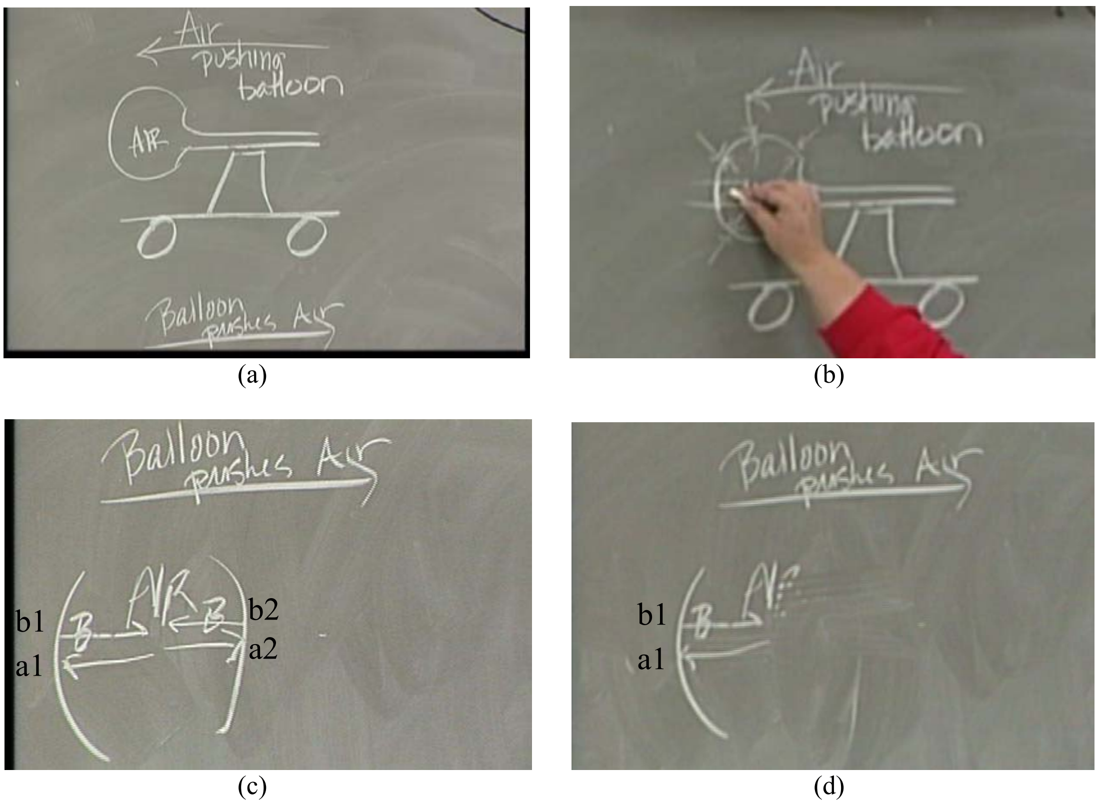

Figure 1. Teacher's "forces in balloon" drawings: (a) balloon car with force arrows, (b) car with balloon segment opposite straw highlighted, (c) balloon walls when balloon is closed, and (d) balloon walls when balloon is open.

She then erased the right arc, saying that if it disappeared, so would two of the arrows, and erased arrow b2, then arrow a1. She paused, then corrected herself, saying "whoa, somebody disappeared who shouldn't have disappeared." She redrew the arc and arrows and started over. She again erased the right arc, then arrow b2 and next, arrow a2 (Figure 1d) and explained,

> So that whole side is gone *(indicates right side)*, right? So then just this bit *(draws two lines isolating part of left arc)* is where I have force. So I've got some air streaming out this way *(draws thick arrow to right)*, and I've got some air still pushing here *(traces over arrow a1)*.

She erased this representation, then directed students' attention back to the balloon in the drawing of the car (Figure 1b), concluding,

> So you've got the air being pushed in this direction by the balloon *(moves chalk to right)*. But there's still some air left that's pushing on your balloon *(gestures with chalk to left)*. So you get forces in both directions, do you see why?

In summary, she then asked the class, “What makes your car go?... What is it that's pushing in that direction *(points left)*?” One of the students offered, “Maybe the rest of the air that's still pushing back on the balloon?” To which the teacher responded, “Exactly!”

Tensions & tradeoffs in the “forces in balloon” lecture

We focus on *tensions* related to the teacher’s efforts to communicate a model of balloon-car propulsion in terms of forces – i.e., linking the design to the science. We further query why a lecture was used to deliver a model to students in a project-based, inquiry classroom – i.e., why developing the model was not itself an object of student inquiry. We offer an explanation for the lecture mode in terms of *tradeoffs* in the activity design.

Tensions in modeling and representing the forces

The “forces in balloon” lecture challenged the teacher to develop and communicate an *explanatory model* of the science that accounted for balloon car propulsion. As she noted in the earlier quote, “the balloon engine, as an entity, is complicated for kids; it’s complicated for adults” (Reflection, 11/30/01). It was difficult for Ms. Harding herself: “I ‘get’ the balloon. But it took me awhile.... I just had to stew over it for awhile.... And then I got the point where I ‘got’ where things were going on” (Interview, 08/09/05). Newton’s Third Law, or the concept of forces in pairs, provided the explanatory model of balloon propulsion. But “once a model has been constructed, the next step is to find a representation that communicates the ideas of the model” (Carpenter & Romberg, 2004, p. 16). Ms. Harding still faced the challenge of explaining the model to students; “I thought, ‘okay I get the basic thing, but how am I going to turn around and explain this to fourteen year olds?’” (Interview, 08/09/05). The teacher’s efforts to represent the forces-in-pairs model of balloon-car propulsion in this video episode exhibit two notable tensions: representing an abstract science concept in a concrete design context, and finding an appropriate amount of complexity to include in the model.

<u>Modeling an abstract concept in a concrete artifact</u>

The first tension is created by the need to represent forces in the context of the balloon car. The teacher found herself up against a core demand of engineering design: re-representing *abstract* scientific knowledge in the *concrete* circumstances of the artifact under design (e.g., Gilbert, 1992; Layton, 1993). Engineering design requires an intermediate form of knowledge between the abstract and concrete. As Ms. Harding pointed out in her earlier quote, that the balloon car is an embodiment of forces in pairs did not by itself make the concept concrete. “Even though it’s [the balloon car] sitting in front of them – we think we’ve given them a tool, but it’s [the forces] still very abstract to them” (Ms. Harding, Reflection, 11/30/01). She was left with the challenge of finding a way to represent the abstract in the concrete.

Ms. Harding moved from her first representation through a second and a third (Figures 1a-1c), seeking a level that would communicate the concept to students. As she progressed, she focused in on narrower regions of the original drawing, “blowing up” sections while representing them more abstractly. In effect, she stepped up in levels of abstraction from the first through the third drawing, then reversed direction, increasing in levels of realism until she arrived back at the artifact itself and asked students, “What makes your *car* [italics added] go?” (Lecture, 11/30/01).

Afterward, Ms. Harding questioned the value of the representations she had employed. Reflecting on the lecture a few days later, Ms. Harding reported, “I went back and I looked at everything we'd done and they [the students] were confused” (Reflection, 12/04/01). After viewing the video of the lecture, Ms. Harding said, “I could tell when I did it I wasn’t happy with it. It wasn’t making the points I wanted made or was confusing them to some point” (Interview, 08/09/05). The teacher struggled to explain the forces using different representations of the balloon car and, while she thought her explanation eventually “got there” (Interview, 08/09/05), she noted, “I don’t draw as many pictures with it [the balloon anymore] because I think the pictures are more confusing” (Interview, 08/09/05).

The day after the lecture, Ms. Harding revisited forces in the balloon, abandoning balloon-car drawings for a set of abstract representations provided in the curriculum that included motion storyboards, free-body diagrams, and net force diagrams. However, as a researcher on the curriculum development team noted, “there’s a gap in-between those two [the abstract representations and the car itself] that another representation would facilitate, more understanding or a deeper understanding" (Researcher 54P, Interview, 05/04/05). It was at this level that Ms. Harding had attempted to communicate with her balloon-car drawings. And while Ms. Harding thought her explanation had been confusing to students, upon reviewing her third drawing (Figure 1c) in an interview four years later, she commented, "I may have to pull that back in" (Interview, 08/09/05), implying she still lacked an effective representation to link the balloon car and the forces operating within it.

The set of abstract representations Ms. Harding returned to work well for explaining the concepts at a high level, but it appears representations at *multiple* levels of abstraction are needed to communicate the model of forces-in-pairs in the balloon. The tension exhibited in Ms. Harding's lecture indicates a need for another, intermediary level of representation that would complete the link between the abstract and the concrete. Some research in physics education has also recognized the need for this link in teaching about forces and has demonstrated the value of intermediate-level diagrammatic representations that may support the engineering design context as well. System schemas (Hestenes, 1996) and the symbolic representation of interactions (SRI) notation (Jiménez & Perales, 2001) are two approaches that focus specifically on Newtonian forces. Because of the design-based context of instruction, however, Ms. Harding was attempting to do more than explain Newton's Third Law in the context of the balloon car; she was also attempting to lead students to a form of technological knowledge (Rophol, 1997) that translates the science law into a specification for designing their cars. Ms. Harding's next statement after the "forces in balloon" explanation was "so, if you could have more area here *(points to area of balloon opposite straw)*, then you'd have more space where that push was happening" (Lecture, 11/30/01). Making this further link into technological knowledge provides yet another representational challenge; the curriculum provides support for doing so (Ryan, Camp, & Crismond, 2001), but a fuller discussion must be left for another paper.

Modeling complexity

A second, related, tension in the lecture is finding the appropriate level of *complexity* to include in the model of "forces in balloon." In scientific and engineering modeling practice, "identifying key features to be modeled focuses attention on what is essential and strips away what is not, thereby reducing the complexity of the original situation" (Carpenter & Romberg, 2004, p. 16). In her "forces in balloon" explanation, Ms. Harding iteratively applied this concept as she stepped through more and more pared-down representations of the situation in the lecture.

Earlier in the lecture Ms. Harding had started to draw forces in the balloon, but stopped herself, saying "We're not going to draw this.... There's some forces that ya'll don't know about, ... we're not drawing this one" (Lecture, 11/30/01). When she did later draw the balloon (Figure 1a-1c), she included only the forces of balloon-on-air and air-on-balloon, ignoring, for example, more complex elastic forces in the balloon. And while Figure 1b included forces operating all around the balloon, her third drawing (Figure 1c) reduced them to two sets of pairs on opposite sides of the balloon, representing the operative forces as a summative set of pairs. As she stepped through her drawings Ms. Harding also whittled away at the balloon car itself until she arrived at a representation depicting the balloon engine with only two lines.

Even a seemingly simple artifact can embody complexity that has to be reduced to focus on desired concepts under study and avoid others considered beyond the scope of the course or of student understanding. In seeking a representation that would effectively communicate the "forces in pairs" model to students, Ms. Harding iteratively reduced complexity in her drawings until the balloon car became two lines and the forces under consideration, a pair. The tension existed in finding the right level of complexity to represent the model without losing too much of the context it meant to explain. Finding the right balance is necessary for effective use of models in teaching; explanations that include irrelevant entities and structures will not aid student understanding (Gilbert, Boulter, & Rutherford, 1998).

Tradeoffs in the activity design

Taking a step back and considering the function of the lecture in this design-based, inquiry classroom, one might question why the lecture existed at all in the activity, i.e., why developing their own explanatory models of forces in the balloon was not a subject of student inquiry itself, assuming it would lead to deeper understandings of "forces in balloon." We offer an explanation in terms of *tradeoffs* in the activity design. Two factors are especially relevant. First, a constant mediating factor in project-based, design-based, or inquiry science classrooms is *time*, of which there is never enough. The teacher acknowledged time to be a challenge for her, "I'm really bad about time. It takes me forever.… I just can't seem to condense it" (Interview, 08/09/05). A second factor is the *difficulty* of understanding how "forces in pairs" propel the balloon: "That's it with the balloon, is that it is, it's confusing. They [students] don't really get how it works" (Ms. Harding, Interview, 08/09/05). The teacher summarized her decision that led to the lecture:

> I don't know, maybe it's just I'm not a good inquiry teacher in that I just can't let them discover this all on their own. But I just feel like this is one of those times where you have to step in and just show them. (Ms. Harding, Interview, 08/09/05).

Kimbell, Stables, & Green (1996) provide a framework of tradeoffs in design-based curricula that helps explain the lecture. They point out design tasks require a balance between a) product purposes and teaching & learning purposes of the task, b) an open, ill-defined context and a highly-specified task, and c) teacher control and student autonomy. Specific to the "forces in balloon" explanation was a need to balance product purposes, i.e., designing and building a balloon car, with learning purposes, i.e., understanding forces in pairs. While designing a car was intended to facilitate understanding forces, the design challenge actually limited the extent to which the curriculum could be suspended to allow students to develop their own explanatory models through further inquiry. Time limitations required the curriculum to continue to move forward to meet the overarching challenge to students of designing and building their optimal balloon cars. According to one of the curriculum developers, "there is an end that we want you to get to, not just in the content understanding, but in the actual performance of the vehicle you designed" (Researcher 55A, Interview, 05/05/05). Foregoing the challenge would also have meant forfeiting what were perceived to be some of the primary benefits it brought to the classroom: its role in structuring the inquiry and motivating students to learn the science.

Additionally, having students understand "forces in *pairs*" was more important than having them understand "forces in *balloons*." Asked what she expected students to know as a result of the balloon car challenge, the teacher replied, "I want them to have a good idea about forces occurring in pairs" (Interview, 08/08/05). The balloon-car challenge primarily afforded students a contextualized understanding of "forces in pairs." Had the primary objective of the activity been inquiry into "forces in balloon," the task more open-ended, and the approach more student-driven, it might have been feasible for the class to take time for students to develop their own models of what was driving their balloon cars forward. However, some DS curricula have found design tasks that are more open and ill-defined and student-driven produce tensions that frustrate students rather than facilitate their learning (Hmelo, Holton, & Kolodner, 2000; Kolodner et al., 2003). Finding the "right" balance among Kimbell, Stables, & Green's (1996) dimensions requires taking into account myriad mediating factors in the DS activity; achieving a balance necessitates tradeoffs.

Conclusion and Implications

The "forces in balloon" explanation provides a window into some of the tensions and tradeoffs that can arise for teachers in the DS classroom. Engineering design is not an unproblematic context for teaching and learning science. Engineering design introduces tensions in that it requires new representations, at multiple levels of abstraction and appropriate levels of complexity, to link science concepts to the concrete circumstances of design. It demands new PCK for teachers that includes skills in scientific/engineering modeling; an ability to facilitate students' explanatory models, whether by direct instruction or through inquiry; and an understanding of and means for representing targeted science concepts in the concrete circumstances of an artifact under design. The teacher's choice of a lecture for communicating the explanatory model for balloon-car propulsion reflects a tradeoff resulting from decisions made in instructional design. Design-based activities require striking a balance along several dimensions in response to such mediating factors as time and goals of the activity. Regardless of the instructional method chosen for building explanatory models, teacher professional development in the DS context must supply teachers with tools and opportunities to develop the ability to conceptualize and communicate models at varied, appropriate level(s) of abstractness and complexity. The present study indicates providing teachers with opportunities to reflect on practice can advance this agenda.

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