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"What's the Science Behind It?" The Interaction of Engineering and Science Goals, Knowledge, and Practices in a Design-Based Science Activity

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This manuscript is based on data used in Mary J. Leonard's doctoral dissertation. An earlier version of the introduction and theoretical framework was published in the Swedish *Journal of Research in Teacher Education* (Leonard, 2005); since that time engineering practices and models and modeling were incorporated into the framework. Earlier analyses of the data were presented at the International Conference of the Learning Sciences (Leonard & Derry, 2006), the National Association for Research in Science Teaching international conference (Leonard, 2007), and the Annual Meeting of the American Educational Research Association (Leonard & Derry, 2007). Correspondence should be addressed to Mary J. Leonard, Department of Education, Montana State University, Bozeman, MT 59717. Email: mleonard@montana.edu.

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"What's the Science Behind It?"

The Interaction of Engineering and Science Goals, Knowledge, and Practices in a Design-Based Science Activity

Mary J. Leonard and **Sharon J. Derry**

Curriculum developers in the United States have been drawn to engineering design activities as a means of providing students real-world contexts for learning science concepts (e.g., Fortus et al., 2002; Kolodner, 2002; Sadler, Coyle, & Schwartz, 2000; Seiler, Tobin, & Sokolic, 2001). A common implementation in middle schools is having students build miniature cars powered by various means (for example, rubber bands or balloons) as a way to learn about forces of motion and friction—key physics concepts. In these settings, engineering design is typically used to scaffold science learning, as well as to support such general education goals as decision-making and working in teams. The attractions of this approach are great. Design activities motivate students (Kelly & Heywood, 1996; Roth, 2001) and fit well with important learning theories: the cognitive constructivist view that individuals construct knowledge from their experiences (Piaget, 1985), the social constructivist view that students learn through meaningful activity with others (Vygotsky, 1978), the constructionist view that students learn by building artifacts (Papert, 1993), and the pragmatist philosophy that values design-based learning (Dewey, 1933; 1938). Furthermore, education standards have emphasized teaching science in rich, authentic contexts (American Association for the Advancement of Science [AAAS], 1993; National Research Council [NRC], 1996), which engineering can provide. In a significant recent move, the new *Framework for K-12 Science Education* (NRC, 2011) officially integrated engineering into science education and called for K–12 students being given "the opportunity to carry out scientific investigations and engineering design projects related to the disciplinary core ideas" (pp. 1–2).

While engineering and science are highly interrelated, there are potential drawbacks to using engineering as a means for learning science as it connotes a view of engineering as applied science (Leonard, 2004). In reality, engineering design has significant epistemological distinctions in its goals, activities, and knowledge that make it not a simple "plug-and-play" context for science learning. That is not to say it is inappropriate to combine science and engineering in classrooms; to the contrary, the domains are interdependent, a feature on which learning activities can and should capitalize (Barlex & Pitt, 2000). It does mean, however, that because of distinctions between science and engineering practice, it is important to attend to their divergences as well as their synergies and to construct an understanding of their relationship into the curriculum.

Design in the Science Classroom

Educational researchers studying design-based science activities have observed students' difficulties linking their designs to the science concepts targeted for learning. In a "Learning by Design" (LBD) instructional unit on preventing coastal erosion, Puntambekar and Kolodner

(2005) found students needed help "relating the science they had learned ... to their designs" (p. 5). In his investigation of people tasked with redesigning a mechanical household device, Crismond (2001) noted "naïve designers made few connections from their work to key science ideas" (p. 791). Summarizing their study of a RoboLab curriculum, McRobbie, Norton, and Ginns (2004) advised teachers "that students will not necessarily make the links between the science ... [and their designs simply] by engaging in the activity. Some students will require specific scaffolding in order to see the science" (p. 6). One approach to providing such scaffolding for students introduces tools, curricular structures, and/or pedagogical approaches that require students to justify their design decisions with causal explanations based on the relevant underlying science (Kim, 2002; Puntambekar & Kolodner, 2005; Roth, 2001; Ryan, Camp, & Crismond, 2001; Schauble, Klopfer, & Raghavan, 1991). To develop such causal explanations, students carry out systematic investigations into science principles operating in their designs. This approach fits with studies that describe the practices of engineering design as involving modeling and experimenting of the same kind used in scientific inquiry. However, we hypothesized that tensions arise in design-based science classrooms due to differences in the qualities and purposes of engineering versus science (Bucciarelli, 1994; Rutherford & Ahlgren, 1990; Schön, 1983; Vincenti, 1990).

Gardner (as cited in Barlex & Pitt, 2000) identified several opposing views of the relationship between science and engineering. The first was the *interactionist* view that holds science and engineering are distinct but are "in a dialectical relationship, with each informing and being challenged by the other" (Barlex & Pitt, 2000, p. 16). Other views were the *engineering as applied science* view in which science drives engineering, the *demarcationist* view that science and engineering are strictly independent, and the *materials* view that engineering drives science. Consensus among scholars who study engineering practice is that the applied science view is inadequate for describing the nature of engineering design, and, moreover, that the interactionist view is most appropriate. In considering the reflective practice of designing engineers, Schön (1983) noted while they make use of scientific knowledge to solve problems, "large zones of practice present problematic situations which do not lend themselves to applied science" (p. 308). In Bucciarelli's (1994) ethnographic report on designing engineers, he asserted that the viewpoint that the principle task of engineering design is to apply science knowledge "misses the complexities of alternative forms and paths to a design, … ignores the diverse interests of participants in the design process, … and fails to acknowledge the indeterminacy of technical constraints and specifications" (p. 185).

Different views of the science-engineering relationship are manifest in the different positionings of engineering design in the science classroom. Research into teachers' and students' conceptions about the nature of engineering design reveals a predominant view of engineering as applied science (AAAS, 1993; NRC, 1996; Lewis, 1992). Those who view engineering as applied science may treat engineering primarily as a means for illustrating the applications of science. However, those with an interactionist view distinguish between engineering and science goals and means. Curriculum designers who establish the requirement that students carry out experiments to investigate the science principles behind their designs may (tacitly or explicitly) embrace an interactionist view, but this alone may not fully ameliorate the potential tensions in the enacted design-based science activity.

The Present Study

In light of educators' and education researchers' interest in design-based contexts for science, it is important to improve our understanding of what happens in the enacted curriculum, to enable us to more effectively capitalize on design for science learning. Toward that goal, the present study investigated a snapshot of a design-based science curriculum, an early version of an LBD (Kolodner et al., 2003) curriculum unit that employed an engineering-type design challenge as the means for students to learn science concepts as well as skills in common to both science and design. Analysis focused on video recordings spanning 2 weeks in an eighth grade talented-and-gifted classroom in a suburban area of a large southern city. In the unit under study, students were challenged to build a balloon-powered miniature car to travel "along a path as straight and as far as possible" (Crismond et al., 2000, p. 86). Students worked in small design teams of three or four and also took part in whole-class sessions for discussion, lecture, and peer presentations of designs and experimental results. We studied the work of the teacher and students in this classroom from a vantage point that acknowledged epistemological differences between science and engineering, specifically examining the interaction of design and science goals, practices, and knowledge in the enacted curriculum, guided by the following orienting questions:

1. How do students and teachers reconcile or integrate goals of learning science concepts and designing/building balloon cars?

2. How do the science and design goals interact in, or determine, their actions?

3. What affordances and constraints does the enacted activity present for students to develop understandings of targeted science conceptual knowledge?

The present study looked at the LBD classroom through an *epistemological* lens, taking a *sociocultural* approach through activity theory and discourse analysis, to examine the classroom activity system. In the course of analysis, *models* and *modeling* emerged as constructs that accounted for much of the work required of teachers and students. Next we describe each of these elements as parts of our overall theoretical and analytical framework.

Theoretical and Analytical Frameworks

Epistemology of Engineering Relative to Science

Contemporary philosophers, sociologists, educators, and reflective practitioners of engineering and technology maintain that, while there are similarities between science and engineering, there are key epistemological differences between the domains' goals, practices, and knowledge.

Goals. Put simply, the goal of engineering is to create artifacts that meet human needs or wants; the goal of science is to develop knowledge and understanding of natural phenomena (Sparkes, 1993b; Rutherford & Ahlgren, 1990; NRC, 1996). As Vincenti (1990) described in his historical analysis of aeronautical engineering projects, “for engineers, in contrast to scientists, knowledge is not an end in itself or the central objective of their profession. Rather, it is ... a means to a utilitarian end” (p. 6). With their different goals and orientations come different beliefs and theories about the nature and limits of knowledge and its acquisition, as well as different norms for accepting assertions. In his account of the philosophy of technology, Mitcham (1994) observed the questioning of technological theories to be qualitatively different from the questioning of scientific ideas, in that “the assumption among technologists is not that technological theories are true but that they work, and that the works to which they give rise are good or useful” (p. 96).

Practices. Vincenti (1990) noted “the epistemological distinction [between science and engineering knowledge-generating activities] is one of priority and degree of purpose rather than method” (p. 227). Engineers engage in *modeling* and *experimenting* of the same kind used in scientific inquiry, albeit with differences in their qualities and purpose.

The work of designing engineers depends on generating and using the same sort of abstract and reductionist models prevalent in science (Bucciarelli, 1994). The practice of modeling involves successive cycles of constructing, evaluating, and revising models through observation and experimentation. Models necessarily represent only selected features of real systems or phenomena, ignoring or stripping away others that are not relevant for the model’s purposes (Carpenter & Romberg, 2004; Gilbert, Boulter, & Rutherford, 1998a; Hestenes, 1996). Scientific models provide designing engineers a reliable source of information on which to base their designs (Sparkes, 1993a). A key difference is that, for engineering use, models derived from science concepts need not explain the natural phenomenon underlying an object’s behavior, but they need to represent the object accurately enough to explain and predict its behavior. And science concepts are often necessary but not sufficient for engineering models, which must also take into account the concrete materials of the situation, such as the operational environment, materials, and tolerances and limits (Sparkes, 1993a).

The use of experiment figures prominently in both science and engineering design. AAAS (1993) provides a description of experiment’s roles in each domain. In a science role, experiments are used to understand the relation between cause and effects, to show that theories fit the data, or to discover something. In an engineering role, experiments are used to produce a desirable outcome, as feasibility tests to demonstrate that designs work and reliably so, or to cause something to happen. Engineers employ experiments in both scientific and engineering roles; experiment may be aimed at testing a particular hypothesis (scientific inquiry) or at achieving a particular technological effect (engineering design) (Schön, 1983).

Knowledge. Bucciarelli (1994) noted designing engineers rely on their understanding of the principles and concepts of their discipline, for example, mechanics, chemistry, or electricity, to make their designs. Scientific principles, such as the law of conservation of energy or properties of surface chemistry, provide engineers with understandings of the behavior of objects. Scientific and mathematic principles may provide the underlying form and basis for an engineer's work or they may be drawn on to understand and solve emergent design problems. At times, designing engineers "see" objects in terms of abstract, often idealized, scientific and mathematical concepts and relationships; for example, stresses and strains, circuit relationships, energy flow, or momentum. At other times, designing engineers talk about the concrete materials of the situation; for example, the performance of a particular photovoltaic module. We next discuss forms of knowledge unique to engineering, some adapted from science and others generated within engineering.

***Adapting science knowledge for engineering*.** In addition to scientific (and mathematical) principles, engineering design requires an intermediate form of knowledge between abstract scientific knowledge and specific device knowledge (Gilbert, 1992; Layton, 1993; Levinson & Murphy, 1997; McCormick, 1997; Schön, 1983). In his taxonomy of engineering knowledge, Ropohl (1997) referred to this form as *technological laws*, built either by adapting abstract natural laws to the real technical process at hand, or by generalizing from empirical results. Layton (1993) provided another example, in which scientists and technologists may use different conceptual models for the same phenomenon, based on their differing goals:

> A science teacher, aiming to develop an understanding of the kinetic-molecular theory of heat, might deal with the conduction of heat through materials in terms of molecular motion. For the technologist, engaged in the task of improving the insulation of building and reducing heat losses, a simple fluid flow model of heat might be adequate for most work (p. 58).

Layton went on to identify several additional ways academic science knowledge often needs to be reworked to be useful in the specifics of engineering design tasks. First, what is needed to solve an engineering problem often must be drawn from several diverse academic sciences and then repackaged in a way suitable for the task at hand. Kanter, Kemp, and Reiser (2001) encountered this situation when they searched for a biomedical engineering task that would "promote students' meaningful understanding of the human biology content and concepts we were targeting" (p. 3). They found that typical biomedical device projects, like developing a glucose sensor or a wheelchair, would require synthesizing knowledge from chemistry, electricity, materials science, and mechanics, in addition to human biology. The curriculum designers opted instead for a "lower tech" design context that focused more exclusively on their targeted human biology concepts—having students redesign their school lunch choices to meet their bodies' energy needs.

Next, science knowledge must sometimes be reconstructed or reorganized into a form more appropriate to the engineering design context. Layton gave as an example a situation where public health engineers found the scientific classification of water- and excreta-related diseases in terms of causal agents (viruses, bacteria, protozoa, and helminthes) not suitable for developing a disease prevention program. They had to reorganize the information according to environmental transmission patterns of the diseases, a classification not dependent on causal agents.

Finally, solving engineering problems requires “building back into the situation all the complications of ‘real life,’ reversing the process of reductionism” (Layton, 1993, p. 59) and decontextualization that have enabled the advancement of science knowledge. For example, most physics theories carry the assumption of a frictionless system when the theory is not dealing specifically with the phenomenon of friction, whereas in many engineering design situations the effects of air resistance and friction are integral to successful designs.

Engineering design knowledge beyond science. There is a still larger body of engineering knowledge beyond that adapted from science. In addition to the technological laws discussed earlier, Ropohl (1997) identified several other types of engineering knowledge. First, Ropohl noted “engineering tends to transform technological laws and empirical generalizations into functional rules, which means specifying what to do, if a certain result is to be attained under given circumstances” (p. 68). *Functional rules* might be expressed cookbook-style. Expert heuristics (Gigerenzer, 2002), as well as the construction templates that embodied the knowledge needed to build Gothic cathedrals (Turnbull, 1993), fit this category. Next, the category of *structural rules* concerns the assembly and interaction of components of a technical system. These rules may be based in scientific knowledge; for example, rules for connecting electrical components that derive from Ohm’s law. Others, such as rules for reinforcing a framework construction, may originate in historical and current practice. The next knowledge type, *technical know-how*, includes tacit and implicit knowledge as well as specific skills of one’s practice. This is the knowledge of expertise (Larkin et al., 1980), built up from thorough practice and experience of many, many cases. Schön (1983) referred to this kind of knowledge as “knowing in action” and it includes patterns of action—an engineer’s technical repertoire and “feel” for the stuff she or he is dealing with. The final type of conceptual knowledge identified by Ropohl was *socio-technical understanding*. This kind of knowledge has begun to transform engineering design, opening it to “systemic knowledge about the relationship between technical objects, the natural environment, and social practice” (Ropohl, 1997, p. 70).

Implications for the classroom. What do the existence of distinct science and engineering goals and a broad and unique body of engineering knowledge imply for design-based science classrooms where the objective is to provide engineering contexts for understanding science concepts?

1. It takes more than science conceptual knowledge. While technological knowledge may not be among that targeted for learning, it will come into play, unbeckoned, during the design activity. For example, students will grapple with problems related to construction of their artifacts, attempting to work through their lack of pertinent functional rules, structural rules, or technical know-how. If teachers or curriculum developers are unaware of or fail to acknowledge the spectrum of knowledge that designing engineers draw on, they may perceive such problems

to be diversions from the "real" goal of a contextualized understanding of science concepts.

2. Science conceptual knowledge may need to be reworked to be relevant to design tasks. Knowledge in a form used or developed in science is not always directly transferable to engineering; students may need to be guided in working at different levels of abstraction; moreover, they may require engineering in addition to science resources.

3. When learning *science* concepts is a desired outcome of the design activity, the need for the science may have to be created or made explicit in the curriculum. This is the area where most scaffolding is currently directed—pushing students to explain behavior in science terms. Because the test of engineering success is "does it work?" rather than "can you explain why or how it works?" engineering tasks can often be successful without understanding the cause-and-effect (the science) of an artifact's behavior. More scaffolding will be necessary when the science is not essential to the design task (Layton, 1993).

In sum, to fully recognize the challenges we are setting for students and teachers and to build better bridges between science and design in the classroom requires that we more fully acknowledge in the curriculum similarities as well as distinctions between science and engineering.

Models and Modeling

While the curriculum under study did not explicitly include modeling as a science or engineering practice, it emerged during our analysis as a framework that accounted for the work that both the teacher and the students had to do to understand and communicate the science behind balloon car propulsion. As discussed above, models and modeling are central practices not only in science but in engineering (and mathematics) as well. Models and modeling in engineering design are often thought of as building *physical* models of an artifact under design. However, engineering design also requires *conceptual* models and modeling of the same sort used in science practice (Bucciarelli, 1994; Hestenes, 1996; Sparkes, 1993a). National K-12 science and technology education standards (AAAS, 1993; NRC, 1996, 2011; International Technology Education Association [ITEA], 2007) and discussions about engineering standards (Katehi, Pearson, & Feder, 2009) promote models and modeling in the classroom, as do science and design and technology education researchers (e.g., Carpenter & Romberg, 2004; Gilbert, Boulter, & Elmer, 2000; Hestenes, 1993; Lehrer & Schauble, 2006; Passmore, Stewart, & Cartier, 2009; Windschitl, Thompson, & Braaten, 2008).

Nature and types of models. Gilbert et al. (1998a) distinguish between *mental models,* the personal, private representations of a phenomenon (e.g., Gentner & Stevens, 1983; Johnson-Laird, 1983), and *expressed models*, versions of individuals' mental models conveyed in Discourse. This study focuses on the public and more accessible expressed models. Our representations of students' and teacher's expressed models are themselves models, with some (unknown) degree of fidelity to those they seek to describe. However, there *is* correspondence between mental and expressed models, and sociocultural theory tells us that Discourse is the expression of cognition, so our results can reliably reveal something about how students are thinking about balloon car motion.

In examining models, we were not concerned with describing the form of students' mental representations (e.g., are they knowledge nets, images?), but only the meaning represented in them. Our definition of a model largely followed Hammer's (1996) presentation of students' expressed conceptions as p-prims (diSessa, 1988, 1993), which (1) involve conceptions that are potentially smaller and more fragmentary than physical concepts, and (2) are not necessarily drawn on stable, stored knowledge structures, but are created in situ and often transitory (also, Johnson-Laird, 1983). Furthermore, we took Johnson-Laird's (1983) stance that models need not be entirely accurate or in complete correspondence with what they model in order to be useful (also, Anderson, Howe, & Tolmie, 1996). Thus, the students' and teacher's models characterized in our analysis may be partial, situational, and incomplete expressions of individuals' understanding of a phenomenon as they are expressed in the Discourse.

Expression of models. Our analytical goal was to uncover the models students and their teacher expressed in Discourse. Gilbert et al. (1998a) asserted that models provide the basis for the explanations students, teachers, and even curriculum developers give in science class; we adopted their typology of scientific explanations in analyzing expressed models in the activity system. The first type consists of science models that have been subjected to the rigors of peer review and acceptance by scientists, called *consensus* models. These comprise one of the main products of science and one of the main forms of knowledge to be learned in science classrooms. Teachers or curriculum developers additionally create *teaching* models (e.g., analogies, diagrams, or demonstrations), specially constructed explanations for aiding students' understanding of consensus models.

Several of Gilbert et al.'s (1998a) explanation types are especially informative in analyzing students' models. One explanation communicates how a scientific phenomenon behaves, providing a *descriptive* explanation, an observational account. Another, the *causal* explanation is at the heart of scientific activity. Scientists use causal explanations "to understand and portray mechanisms that might underlie phenomena" (Carpenter & Romberg, 2004, p. 13). Gilbert, Boulter, and Rutherford (1998b) distinguished between *weak* and *strong* causal explanations in classrooms: the weak form identifies a link between an action and reaction but contains no statement about an underlying science mechanism, the element that is the defining feature of the strong causal form. The final type is the *prediction*, which can be *ordinary* or *scientific*. An ordinary, everyday prediction anticipates how a phenomenon will behave in the future by assuming it will follow the pattern of the past (allowing for random variation). The scientific prediction anticipates that a phenomenon will behave differently from the past "in precise ways as a direct consequence of particular actions taken on the basis of a theory" (Gilbert et al., 1998b, p. 195); it is a scientific, model-based prediction.

Analytical Lenses from Sociocultural Theory

Bakhurst (1988) articulated core tenets of sociocultural theories regarding cognition, language, and activity, which are fundamental to the two analytical frameworks we employed: activity theory and discourse analysis. First, these theories consider language, in its broadest expression that includes action, to be the expression of cognition. Second, they acknowledge language to be social—it operates on the shared meanings that comprise a culture or, analogously, a community of practice (Wenger, 1998), language game (Wittgenstein, 1949/1953), or Discourse (Gee, 1999). Third, members of a culture reciprocally transform and are transformed by the practice or activity in which they engage. And fourth, one's higher-order cognitive operations are developed and shaped in social activity (Vygotsky, 1978), especially in enculturation to a community of practice. This shared perspective of language and cognition provides an entrée for analyzing meaning-making in social activity. As the present study draws on activity theory and discourse analysis, we discuss these briefly in turn.

Activity theory. Activity theory's unit of analysis is the *activity system*, a system of subjects acting on objects to effect a projected outcome, and mediated by social, cultural, and historical factors (Engeström, 1999; Leont'ev, 1978, 1981). The activity system as a network of interacting factors is typically depicted in the triangle diagram represented by the shaded boxes in Figure 1. Activity theory provides a descriptive framework for parsing an activity into its functional components, and exposes an abundance of mediating factors at work in the system. Mediating factors, which reciprocally shape and are shaped by participants' activity, include (1) the division of labor in the classroom, (2) the community of participants whose members may be outside classroom as well as in it, (3) implicit or explicit rules, norms and conventions operating in the classroom, and (4) signs, tools and cultural means that constitute the knowledge, skills, language, and other resources for participants. Parsing the activity—identifying its objects, subjects, projected outcomes, and mediating factors—is an act of analysis that enlightens understanding of the system.

As is the case with all designed artifacts, mediating factors in the implementation environment affect the way the curriculum is enacted in the classroom, allowing the activity to progress in some directions but not in others. Implementing an innovative curriculum like LBD requires negotiating a network of factors that may include the school culture, the teacher's disciplinary knowledge, and new demands it may place on teacher and students. The resulting enacted curriculum is a product of more factors than the designers' intent expressed in the curriculum and supports. Activity theory provides a systematic way of identifying, recognizing, and acknowledging factors that affect the form the enacted curriculum takes in the classroom.

Activity systems are further characterized by what activity theorists have called contradictions, or *tensions*, within and between its components. Tensions are places in an activity system where some of its elements (i.e., mediating factors, subjects, objects, and projected outcomes) are not well aligned. Tensions are recognized as inevitable and as stimuli for the *transformation*, or evolution, of an activity system. Taking the stance that engineering and science have different goals and knowledge predicts that certain tensions might be present in design-based science activity systems.

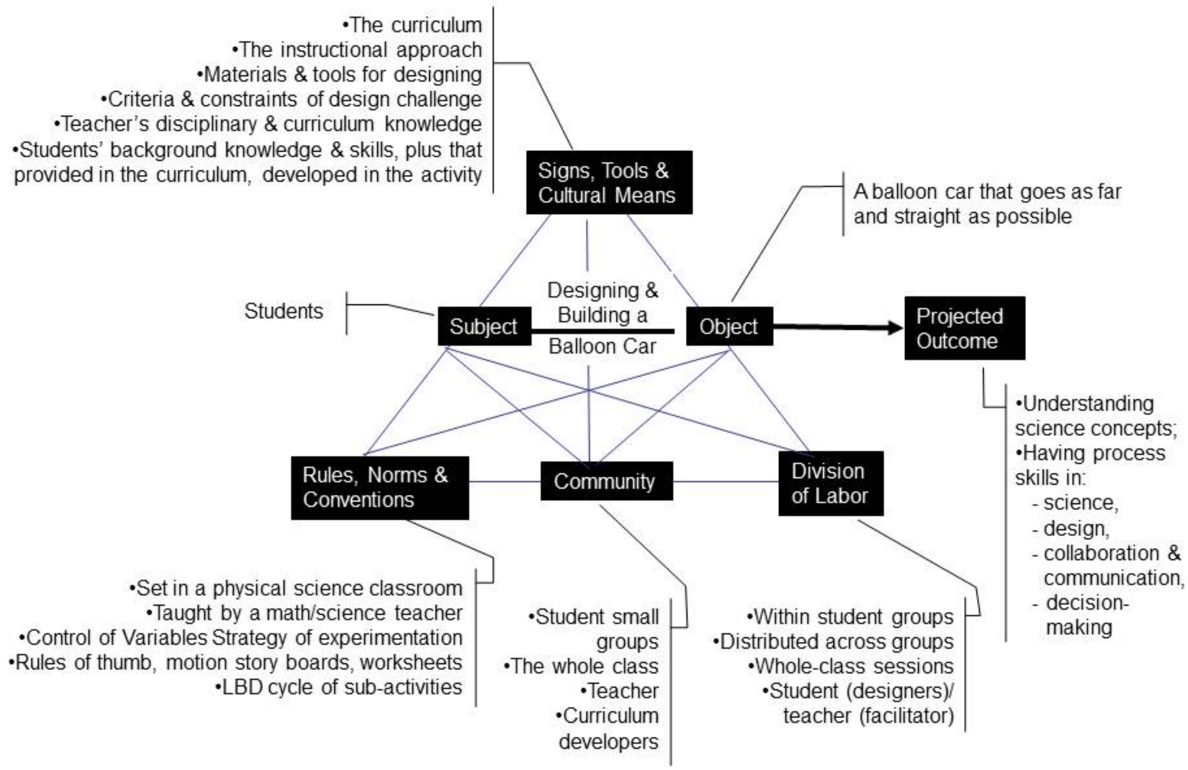


Figure 1. *Activity theory representation of the balloon car activity system in Ms. Harding's classroom.*

Discourse analysis. Discourse analysis complements activity theory, providing evidence and allowing deeper examination of the system. The discourse analysis approach employed in this study is grounded in an ethnographic perspective (Gee & Green, 1998). First, it involves close observation of a community of practice in day-to-day activity, in this case, via video recordings of the LBD classroom. Second, it aims at understanding the classroom from the insider's perspective (or more accurately, multiple insiders' perspectives: students' and teacher's) as revealed through social interaction—classroom dialogue, both discourse and action. And third, analysis focuses on what Gee (1999) calls "big-D" Discourse: language-in-use (discourse) plus all the non-language "stuff" (for example, actions, gestures, posturing, tools, symbols, attitudes, and beliefs) through which people enact activities and identities.

Activity theory and discourse analysis are complementary and reciprocal analytical approaches. Activity theory provided a framework for parsing and talking about the LBD enacted curriculum as an activity system shaped by tensions between the goals, practices, and knowledge of science and engineering. Discourse analysis provided rigor and method for investigating participants' discursive and social practices (Green & Dixon, 1994) in depth as a basis for uncovering their models and modeling processes and how those were influenced by epistemological tensions that resulted from bringing science and design together in the classroom.

Methods and Data Sources

Research Context

The LBD curriculum. We investigated an early iteration of the LBD curriculum as an instance of a design-based science activity system. The LBD curriculum immersed students in design activities to learn science and design skills and concepts (for a detailed story of the curriculum, see Kolodner et al., 2003). A complex of scaffolds and integrated cycles of activities motivated, structured, scaffolded, and sustained students' inquiry through engineering design-type challenges. The balloon-car challenge we investigated was part of an 8-week *Vehicles in Motion* (ViM) unit (Crismond et al., 2000) in which "students learn about forces and motion by redesigning vehicles and their propulsion systems" (Kolodner et al., 2003). Before undertaking ViM, LBD classrooms first engaged in a 3-week introductory unit called the *launcher unit* (Holbrook et al., 2001) that involved students in a series of design and experiment activities intended to enculturate them into the processes of doing design and science.

The ViM unit included three design "mini-challenges," each developed to last an average of 2 weeks. The balloon-car activity was second in the series, preceded by a challenge to design and build a miniature car that coasted down a ramp and followed by a challenge to build a miniature car propelled by a rubber band or a falling weight. Thus, students entered the balloon-car activity having engaged in the LBD cycles of designing and investigating/exploring (Holbrook et al., 2001) and building a "coaster car." Furthermore, like the balloon car activity, the preceding launcher unit and coaster car challenge explored science concepts of forces of motion and friction in different contexts. The curriculum was tightly scripted, providing detailed instructions to teachers for sequencing instructional elements and to students for performing tasks.

Ms. Harding's classroom. The classroom studied was one of Ms. Harding's (teacher and student names are pseudonyms) eighth grade talented-and-gifted (TAG) or honors science classes in a new, well-funded public middle school located in a suburb of a large southern city. The teacher was a white female in her 40s and was in her second year teaching the ViM curriculum. She had taught science on and off for the previous 13 years and was certified in a number of areas, including mathematics, science, and social studies.

To enroll in the TAG science course, a student must have qualified for TAG mathematics. Nineteen students were in the classroom under study: 12 male and 7 female. The majority of the students were white (14); the minority Asian-American (5). The video collection started at the end of November; students had been working in their same small groups since the beginning of the school year in August. Ms. Harding reported that she assigned students to small groups randomly, but made adjustments to separate students she knew did not get along, as well as boyfriends and girlfriends (Retrospective Interview). The five small groups in this classroom were a mix of all-male and male-female membership.

Each small group sat together at one of the five round tables in the classroom. Ms. Harding identified the groups with numbers assigned sequentially from right to left, front to back. The teacher had a desk in the back of the classroom and a laboratory bench at the front. A table, blackboard, and pull-down screen were located to the right of the teacher's workstation. Lower cabinets lined the walls on three sides of the classroom, providing space for storing supplies and small groups' shoeboxes of materials. The cabinets were topped with counters that served as workspaces and as the "parking lot" for students' cars. Above the cabinets posters from students' presentations would, over the course of the activity, paper the walls.

During the unit under study, a researcher from the curriculum development team was present in the classroom to observe the activity, serve as a curriculum resource for the teacher, and capture guided reflections by the teacher at selected points in the activity. Additionally, during the first 2 days of videotaping, the second co-author was present to direct video data collection.

The balloon car activity system. The balloon car unit as enacted in Ms. Harding's classroom is depicted in the activity system diagram in Figure 1. This study took the activity to be the balloon-car challenge as a whole: students and teacher (subjects) engaged in designing and building (activity) a balloon car (object). The ViM student textbook (Crismond et al., 2000) identified the projected outcomes of the activity to be students understanding science concepts of force and having process skills in science, design, collaboration and communication, and decision-making.

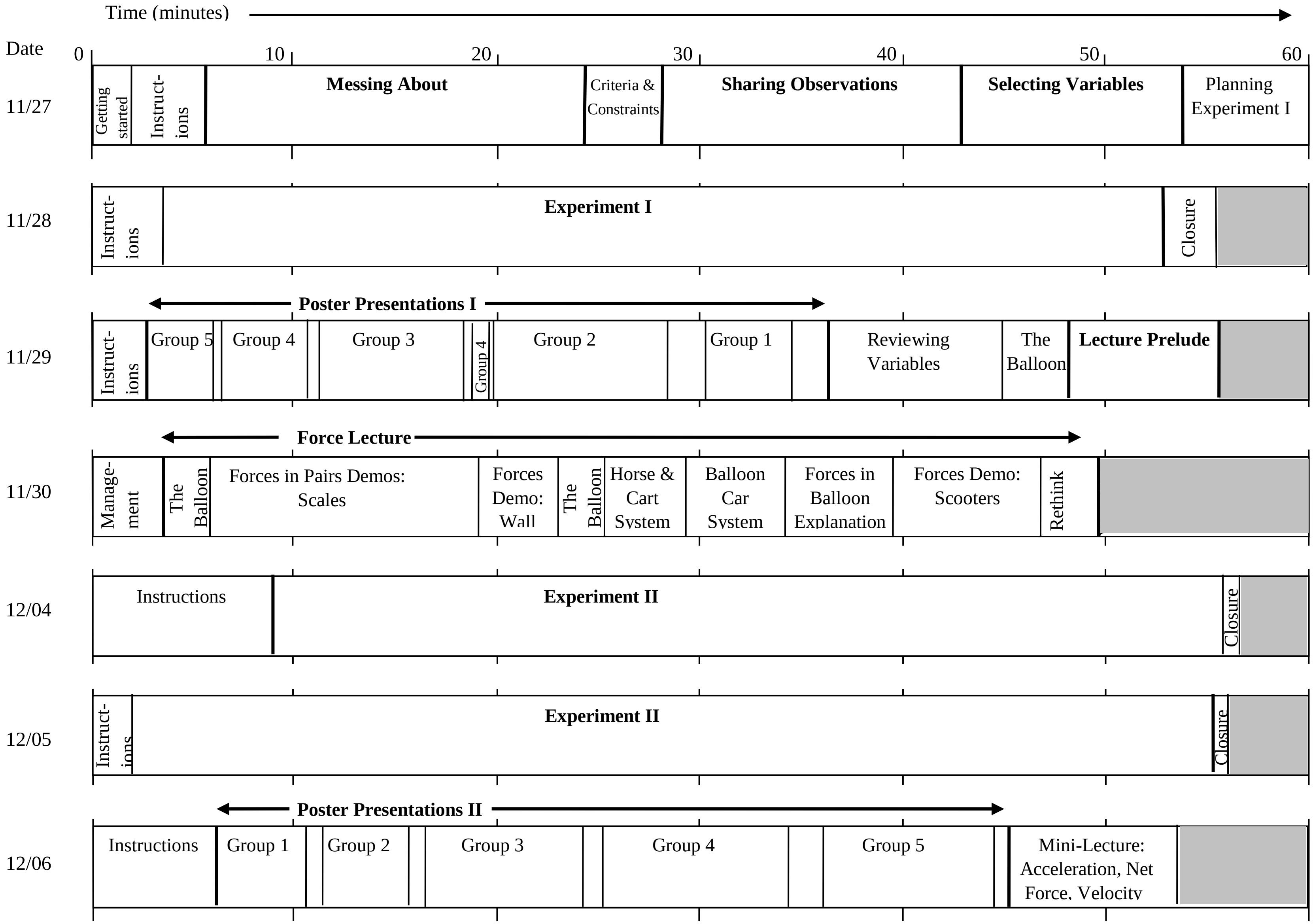


Figure 2. *Timeline for the 7 days of the balloon car activity (patterned after Kelly & Crawford, 1997). Sub-activities are identified in* ***bold****. Each row represents 1 day's instruction; dates of instruction are listed along the left. Unlabeled segments are transitions between group presentations.*

Balloon car activity sequence. Like all LBD challenges, the balloon-car activity in the classroom under study focused on iterations of experimenting and designing in small groups but also included whole-class lectures, discussions, and student presentations. Activity theory identifies a hierarchy of levels in the structure of activities that enabled the identification of *sub-activities*; the sub-activities within the balloon-car activity were identified in the classroom videotapes that provided data for the study and are described in Appendix A. Figure 2 presents the timeline for the video data that covered the first 7 days of the activity. The balloon car activity continued beyond the current video data with small groups directed to apply all they learned about their and others' balloon car designs and science concepts of force and motion to design their optimal balloon cars. Iterations of re-design and presentations would culminate in balloon car performance tests and a summary of the unit.

Control of variables experimental strategy. One of the key processes students learned in the launcher unit, a process central to the sub-activities under study, was what the ViM textbook referred to as "fair testing" (Crismond et al., 2000), also known as the control of variables strategy (CVS) of experimentation (e.g., Chen & Klahr, 1999). CVS seeks to control all but the tested variable so that experimental results may be attributed to its effects, not to random variation or influence of other factors. In the context of balloon cars, a variable was an element of the car's construction that could be configured more than one way. Students built a balloon car by attaching a balloon engine on top of the coaster car from the preceding challenge. The engine was a balloon with a drinking straw inserted through its opening; the other end of the straw was affixed to a Styrofoam cup attached to the car's chassis, as illustrated in Figure 3. The chassis was a small platform with two axles fastened to its underside that connected the four compact discs serving as wheels. Variables that could be tested in experiments included such things as the angle of the straw relative to horizontal and the number of cups stacked on the chassis to elevate the engine.

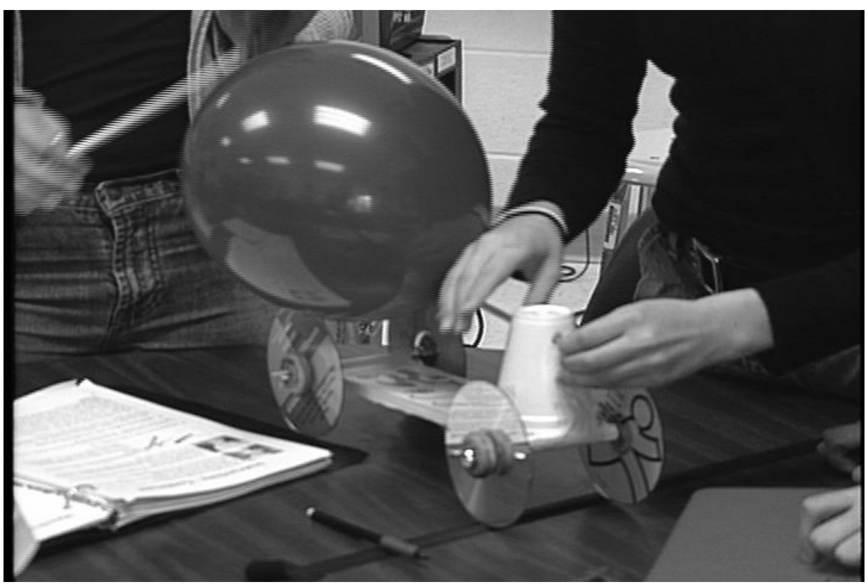


Figure 3. *A balloon car*.

Data Collection

Classroom video. The primary data for our study derived from classroom video, but this was substantially supplemented with document analysis of curriculum-related materials and published papers, and interviews with curriculum developers/researchers and the classroom teacher. Video data covered seven class periods over the first 2 weeks of the 3- to 4-week balloon-car challenge. They included approximately 14 hours of video in the subject classroom—two cameras covering seven 50-minute class periods. Camera A was stationary, capturing the in-classroom actions and focusing on the teacher when she was present. Camera B roved, focusing on individual students and small groups, especially when they were out of the classroom conducting experiments in the hallway. The first audio track continuously recorded the teacher's clip-on microphone; a boom microphone followed Camera B and fed the second audio track. The cameras sampled multiple students and groups during each class session. The corpus of video data included additional footage of guided reflections by the teacher at several times during the balloon car activity.

The original purpose for videotaping the LBD classroom was to create a video case of an innovative science curriculum to be used in a pre-service teacher education program. The planners for the original project for which the video was collected, a group that included the LBD project director and the second co-author, collaboratively selected the days to record based on what they deemed important for representing the design-based science curriculum. Resources for the data collection prevented videotaping beyond the first 7 days. While not collected for the purposes of the present study, the video corpus was nonetheless a rich data source for secondary analysis. Many researchers have found video to be especially amenable for analyses by multiple researchers, most of which is carried out post-hoc (e.g., Kamen et al., 1997; Clarke, 2001). Furthermore, the National Science Foundation is using its funding influence to promote development of video data banks that are available to researchers beyond the projects that collected the data (Derry et al., 2010).

Interviews. The first author interviewed the curriculum developers/researchers and the classroom teacher. Interviews of the curriculum developer/researcher were conducted early in the analysis phase of this project and sought to understand the rationale for the curriculum approach, the story of its development and implementation, and the interviewees' perspectives of how the design activity interacted with science learning. Interviews were semi-structured and tailored to the background of the individual, which ranged from the project director, to original cooperating teacher and later curriculum developer/researcher, to researchers in the classroom. The four curriculum developers/researchers interviewed had been with the project variously from its inception to as recently as a year prior to the interview. Interviews lasted 1½–2 hours each, were conducted over 2 days, took place in the curriculum developer/researchers' offices, and were audio recorded.

The teacher was later interviewed to obtain her reflections on classroom video episodes that were of analytical interest. The interview was semi-structured and conducted in two phases. The first elicited the teacher's background with the curriculum, her experience implementing it, her perceptions of student views about the balloon car activity and the LBD curriculum, and her perspectives on how the design activity interacted with science learning. The second phase sought the teacher's reactions to and reflections on video episodes of her own teaching, as well as on student Discourse. The teacher's retrospective insights were taken as present-day perspectives on her own teaching, not as access into what she was thinking in the recorded moment. We scheduled the two interview phases on subsequent days and each lasted 1½–2 hours. The interview took place in the teacher's classroom the week before the fall semester began and were video recorded. The teacher's perspectives, in addition to those of the curriculum developers/researchers, provided points for triangulation of our analysis, complementary accounts of classroom events under analysis, and cultural and historical contextual information about the classroom and the enacted curriculum.

Documents. Several types of documents were available for study, including the curriculum's textbooks for students from the launcher unit (Holbrook et al., 2001) and the ViM unit (Crismond et al., 2000), the curriculum's teacher guide for ViM (Georgia Tech Research Corporation [GTRC], 2004), assessment instruments used by the curriculum developers/researchers and the teacher, and professional articles published by the LBD team. Document analysis illuminated the goals, context, and history of the LBD curriculum, served as sources for triangulating analysis results or providing complementary accounts, and revealed the framework on which the enacted curriculum was based.

Data Selection and Analysis

We approached data selection both deductively and inductively, identifying and analyzing relevant data in a combination of theory-driven and emergent processes that led to progressive refinement of our research questions (Derry et al., 2010).

We began analysis by viewing the video corpus in time order from the beginning to become deeply familiar with the corpus as well as the activity itself. We employed Transana (Transana, 2006) video transcription and analysis software to index and annotate the activity. Transana enabled us to build collections of video clips that segmented and organized the corpus by major sub-activities (Appendix A) and by individual small groups engaged in independent work. This allowed easier navigation of the corpus, enabling researchers to watch a major sub-activity from start to finish or to view the activity from the perspective of one small group at a time.

In order to find an entry point into the data with regard to orienting questions, during the interviews, the first author asked curriculum developers/researchers where they believed or intended to be places in the activity where design facilitated learning of science concepts. They unanimously identified the Poster Presentations but additionally indicated the Force Lecture (see Figure 2 and Appendix A). We initially focused video analysis on students' Poster Presentations, but found these sessions presented a limited view of students' science ideas of balloon car motion. Students' explanations of their experimental results were sparse if present at all, especially in their first round of presentations. Data on their posters didn't always support their conclusions or they said very little about their experiments, results, or conclusions. In order to "see" the science presented in their posters, to understand how students arrived at the understandings they presented, it was necessary to analyze the Experiments as well.

The Force Lecture was the sub-activity that most pointedly and explicitly drew out the connection between the science and designs for students. While the teacher's efforts to explain balloon car propulsion to students during the Force Lecture, we became aware that the idea of developing and explaining models (Carpenter & Romberg, 2004) provided an explanation for what both the teacher and students were attempting in this class. Developing and explaining models became a core theme (Emerson, Fretz, & Shaw, 1995) for further analysis. This led us to refine the research focus and orienting questions to include investigation of the teacher's and students' expressed models of balloon car motion. We became especially interested in comparing students' pre- and post-lecture expressed models to investigate how students accommodated the scientific explanation of balloon car motion the teacher provided in the lecture.

Three Areas of Analysis

Analysis of the enacted balloon-car activity evolved to consider three areas or topics: (1) the teacher's expression of consensus and teaching models of balloon car motion in the lecture, (2) students' pre- versus post-lecture expressed models of balloon car motion, and (3) tensions in the activity system revealed through Discourse analysis. To facilitate analysis, we divided the activity into three phases: pre-lecture, lecture, and post-lecture (Table 1). We next discuss our approach to each of the three areas of analysis.

Table 1

Activity Phases with their Component Small-Group and Whole-Class Sub-Activities

		Format	
Phase	Sub-Activity	Small Group	Whole Class
Pre-lecture	Messing About	√	
	Sharing Observations		√
	Selecting Variables		√
	Experiment I	√	
	Poster I		√
	Lecture Prelude		√
Lecture	Force Lecture		√
	Lecture Redux (reflection)		√
Post-lecture	Experiment II	√	
	Poster II		√

Analysis of Teacher Models and Modeling

In the Force Lecture, the teacher delivered consensus and teaching models of the science behind the balloon cars during a 4- to 5-minute "forces in balloon explanation" (Figure 2), so we focused a major part of our analysis there. In addition to inductive analysis, our thinking was influenced by Gilbert et al.'s (1998a & b) typology of models and Ropohl's (1997) taxonomy of technological knowledge, which were applied to identify the teacher's consensus model and teaching models and the technological knowledge in her explanations.

Analysis of Student Models

Analysis of students' expressed models of balloon car motion before and after the lecture represents the foundation of this study. We will next describe how we integrated data from small-group and whole-class activities, our coding approach, and the transcription and interpretation of students' models of balloon car motion.

Group 1 and whole class. Analysis required looking within small-group sub-activities and we selected a specific group (Group 1) for that analysis, for no other reason than it was the first group in the list, its number assigned by the teacher according to the seating chart. As it turned out, this group was favored with a high level of coverage in the video data. Although they sometimes worked independently as a small group, Group 1 also participated in the whole-class work (Poster Presentations, lectures, and discussions) that comprised part of the context in which their models developed. Accordingly, we analyzed students' expression of models in two social groupings: Group 1 and Whole Class (which included Group 1). This fit the need for analysis at multiple embedded levels of the activity called for by discourse analysis (Gee & Green, 1998; Kelly & Crawford, 1997) and activity theory (Leont'ev, 1978, 1981), and it also retained the situatedness of Group 1's experience in the whole class.

Coding. We viewed the video of Group 1 from start to finish with a focus on students' explanations, engaging in open coding (Emerson, Fretz, & Shaw, 1995) of *actions* (Leont'ev, 1978) within the sub-activities. Through open coding, several key situations surfaced as places where students appeared to express their ideas about balloon car behavior:

- when troubleshooting their cars during experiments,
- by the variables they selected, controlled, or failed to control
- in their predictions (usually tacit) about the variables they were testing,
- their responses to teacher questioning during experiments or whole-class discussions, and
- in the summaries and recommendations they gave during their Poster Presentations.

The next step developed focused codes (Emerson, Fretz, & Shaw, 1995) that systematically identified in the video data places where students appeared to give expression to their models of balloon car motion. The unit of analysis for focused coding was an *idea* expressed or an *operation* (Leont'ev, 1978) undertaken by an individual. Expression of an idea could span several turns between individuals in interaction, and multiple ideas could be included in one turn. The focused codes were applied to all of Group 1 and whole-class Discourse across the entire activity system that we analyzed.

Focused codes originated in a provisional "start list" derived from the theoretical framework and orienting research questions, but these were revised with iterative analysis (Miles & Huberman, 1994). The start list included Gilbert et al.'s (1998a, 1998b) types of *scientific explanations* and Ropohl's (1997) characteristics of *technological knowledge* (described in the Theoretical and Analytical Frameworks). The operational definitions of these codes were refined to better suit the current context. We added additional codes to cover the operations of identifying, setting, and controlling *variables*, issues with *materials* used to build the balloon cars, expression of *science principles or laws*, and expression of the *operational principle* (Vincenti, 1990) of their cars.

Transcription. Group 1's independent work and the whole-class sessions were transcribed by watching the video of Group 1 and whole-class sessions multiple times, refining the transcript and focused codes each time, and drawing out nuances of action and speech that clarified and further illuminated the activity.

Inductive analysis of models. We consolidated and abstracted Group 1's and Whole-Class' coded ideas and operations into categories using the constant comparative method (Strauss, 1987), by which their ideas and operations were examined comparatively and grouped into categories according to underlying *models*. The category title summarized the common, underlying expressed models of its members. Models were derived separately for pre- and post-lecture phases of the activity, then analytically compared.

Analysis of Tensions

Throughout the analysis of student and teacher models and modeling, we made note of tensions that arose in the activity. The apparently unsupported (by the curriculum) requirement for the teacher to engage in modeling is one example of a tension that emerged during analysis. Other tensions were identified by asking discourse analysis questions (Gee, 1999) such as: Were there conflicting "frames" (Tannen & Wallat, 1987) in students' interpretations of the purpose or goal of the activity?

Validity and Reliability

The study design sought to improve validity of its results through triangulation (Hammersly & Atkinson, 1997) in several forms over the course of analysis, including: deriving models from multiple contexts in the activity, consulting multiple sources of data, a video-stimulated retrospective interview with the teacher, interaction analysis of key video episodes, and consultation with scientists, engineers and other science educators.

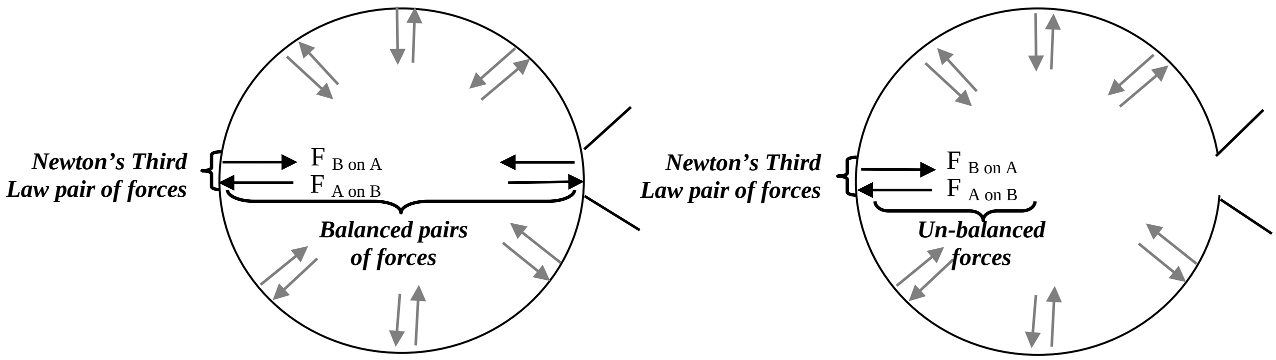
Certain codes turned out to be most relevant to inferring models underlying students' ideas and operations, and we calculated the reliability measures for those codes: strong causal explanations, science principles or laws, technological laws, and functional rules. A second rater (an advanced graduate student) was trained on this discourse coding scheme, and he applied it to a subset of data, achieving a 0.90 (proportion agreement) inter-rater reliability level on the first pass. We further modified the coding scheme in response to issues that arose in discussing codes with the second rater.

Results and Discussion

We present and discuss the results as three interrelated analyses. In Part I we examine the consensus and teaching models for balloon car motion revealed primarily through curriculum materials and the teacher's lecture, because this provides a conceptual context for understanding the analyses of students' models. In Part II, we examine students' expressed models, including changes from pre- to post-lecture phases of the activity. Throughout Parts I and II, we examine the interaction of science and design in the balloon car learning activity, identifying tensions as they arise in the activity system. The transformations these tensions suggest are summarized at the end of each section.

Part I: Consensus and Teaching Models

The curriculum consensus model for balloon car propulsion. In explaining the forces that propelled the balloon cars, the ViM curriculum guide (Crismond et al., 2000) and teacher materials (GTRC, 2004) pulled together multiple science concepts: forces in pairs (used as a precursor to or shorthand for Newton's Third Law of Motion, which states when two objects interact each exerts a force on the other that is equal in size and opposite in direction), balanced forces, net force, and acceleration. Figure 4 summarizes this explanation, illustrating the paired forces of the balloon on the air inside it ($F_{\text{Balloon on Air}}$) and of the air inside on the balloon ($F_{\text{Air on Balloon}}$) in two situations: (a) when the balloon was closed and the car was at rest, and (b) when the balloon was opened and the car was in motion. Because the forces were no longer balanced when the balloon was opened (note absence of force arrows at the balloon's opening), there resulted a net force on the air, which propelled it out the back of the balloon, and on the balloon, which propelled it (and the car) forward. We refer to this as the "curriculum consensus model."



(a) Balloon **closed—**balanced forces; no net force on air or on balloon; no acceleration of air or balloon.

(b) Balloon **open—**unbalanced forces; net force on air and on balloon; acceleration of air and balloon in opposite directions.

Figure 4. *The curriculum consensus model for forces in the balloon that propel the car.*

In our research into a science consensus model for balloon car propulsion (and we acknowledge there is not just one consensus model), we discussed the curriculum consensus model with a science education professor and physicist, a physics professor, and a mechanical engineering professor, all of whom found the explanation acceptable for reducing the complexity and explaining how the balloon propelled the car. However, the scientists and engineer also noted that the issues involved in optimizing the balloon car's performance went beyond the explanation offered by Newton's Third Law and related concepts within the balloon. For example, frictional forces and the car itself complicated the story of balloon car propulsion. In the balloon car activity, students often had difficulty getting their cars to move at all when they began building and testing them, as the example episode in Figure 6 will illustrate. Part of the explanation was that a certain amount of initial force was necessary to exceed the car's static friction and set it in motion; less force would be necessary to exceed the car's sliding friction once the car was moving.

This situation uncovered a new tension in the activity system, in terms of the affordances and constraints of the science knowledge for successfully completing the design challenge. While the curriculum consensus model gave a valid scientific explanation of forces involved in balloon car propulsion, it did not fully account for other factors students would need to consider and explain in order to optimize their balloon car designs.

Models the teacher expressed in the lecture. The most important science concept Ms. Harding wanted students to take away from the balloon car activity was "to have a good idea about forces in pairs" (Retrospective Interview), shorthand for Newton's Third Law of Motion. In Ms. Harding's experience with the curriculum, students did not arrive at an understanding of forces in pairs as the mechanism for balloon car propulsion on their own: "That's it with the balloon, is that it is, it's confusing. They don't really get how it works" (Retrospective Interview). She found a lecture to be the best means for helping students understand the science:

"I just feel like this is one of those times where you have to step in and just show them" (Retrospective Interview).

Because the students were working on a challenge to design a balloon car that would go as far as possible, they needed to learn additional science concepts, beyond forces in pairs, as the curriculum consensus model illustrated. Yet besides understanding *science* concepts in the context of the balloon engine, students also needed the science translated into a *technological law* to guide their balloon car designs. This required the teacher to work at multiple levels of representation, from a highly abstract level using free-body and net-force diagrams (physics notations reflecting direction and magnitude of forces on objects) to a level highly contextualized in the balloon car and its components. It further required her to use a range of explanations, some scientific and some technological. Leonard and Derry (2006) described the teacher's challenges in effectively representing forces at multiple levels of contextualization. Here, we focus on the collection of consensus and teaching models and technological laws she employed in the lecture, identified in Table 2. In the following paragraphs we describe and discuss some of Ms. Harding's key explanations and the tensions the explanations revealed in the activity.

Teaching models. A few minutes into the Force Lecture, Ms. Harding employed a series of teaching models (examples and analogies) to illustrate "forces in pairs" (Table 2), the idea that whenever one thing pushes on another, that other thing pushes back. In one example, she lined up two bathroom scales against a wall and pushed against the outer one; a student read the scales, which registered the same weight. Ms. Harding explained that the outer scale measured the force she was exerting on the wall and the inner one measured the force the wall was exerting on her.

Following the examples, Ms. Harding directed students' attention to the balloon itself, to discuss it in terms of forces in pairs and, as the conversation proceeded, introduced the next teaching model, "no acceleration" (Table 2), as follows (transcription notation is described in Appendix B).

> Ms. Harding: Alright so tell me, look at this balloon ((holds a balloon that is inflated with the opening pinched closed)), what's going on?
>
> Several students: Air is pushing on the balloon.
>
> Ms. Harding: The air is pushing on the balloon.
>
> Several students: And the balloon is pushing on the air.
>
> Ms. Harding: What would you say about the size of those forces?
>
> Several students: [Same] [They're the same] [Exact same].
>
> Student: *No*, I say, I say that force of the air is bigger than the force of the balloon.
>
> Ms. Harding: Wait wait Alisha said something important, go ahead.

> Alisha: They're the same cause there's no acceleration.
>
> Ms. Harding: They're the same, there's no acceleration, we don't see any change in the motion of this balloon, right? So if the forces stay the same, no acceleration. So they're equal size opposite direction.

Ms. Harding capitalized on Alisha's statement in an apparent attempt to make a connection between the forces in the balloon and other elements of the curriculum consensus model, which included the concepts of net force, change in motion, and acceleration. These concepts went beyond Newton's Third Law and derived from Newton's First Law (when the net force acting on something is zero, things at rest stay at rest) and Second Law (a non-zero net force on an object causes it to accelerate). Connecting these concepts was not trivial, and, in attempting to do so, Ms. Harding made a leap that left out an important part of the science explanation and effectively endorsed Alisha's error, that "at points of no apparent motion, forces are sometimes seen as 'equal' and 'opposite'" (Watts, 1983, p. 222).

While the discussion was at a relatively high level in terms of a proposed learning progression in force and motion concepts (Steedle & Shavelson, 2009), it was not completely consistent with the science view. Students could directly observe that the balloon-and-air system was not moving, thus there was no net force and no acceleration. The error came in citing the lack of acceleration of the balloon-and-air system as evidence that the internal forces—of balloon on air and air on balloon—were equal and opposite. In fact, in the balloon, it was the *balanced pairs* of equal and opposite forces that kept the system at rest (see Figure 4). Using the phrase "forces in pairs" may have obscured the fact that there were two types of force pairs relevant to the balloon: (1) Newton's Third Law pairs of forces that always exist when objects interact and that are equal and opposite, and (2) pairs of forces that, when balanced, result in no net force on an object, but, when unbalanced, result in a non-zero net force. Acceleration of the balloon (and the car) would result from a non-zero net force created when one side of the balanced pairs of forces disappeared.

The problem exhibited in connecting these concepts indicated a tension, in that explaining balloon car propulsion required deep, flexible, and integrated knowledge of multiple force and motion concepts, but the teacher may have lacked, or at least lacked on-the-spot access to, the content knowledge required for the explanation.

Communicating the curriculum consensus model. Ms. Harding then introduced the balloon car as a "system" (Table 2), analogous to a horse and cart, then delivered (part of) the curriculum consensus model of the forces responsible for propelling the car. Her focus remained on Newton's Third Law pairs of forces inside the balloon, but, this time, she also alluded to balanced and unbalanced forces.

Table 2

Models and Laws of Balloon Car Motion the Teacher Expressed During the Lecture Phase

Type of Explanation	Teacher's Communication of the Concept
Teaching Models	
Forces in pairs	Forces come in pairs that are equal in size and opposite in direction.
No acceleration	Since there is no acceleration, no change in motion in the balloon when it is closed, it tells us the forces of air and balloon on each other are equal in size and opposite in direction.
System	The balloon car is like the horse and cart; the parts are connected so it becomes a system that works together to make the car move forward.
Force-Acceleration	Little force gives you little acceleration; bigger force gives you bigger acceleration.
Motion storyboards	A set of relatively abstract representations with chapters for each stage in the balloon car's motion, each of which included free-body diagrams, net-force diagrams, and acceleration that described the forces at different points in the balloon car's trajectory.
Teacher's Expression of the Curriculum Consensus Model	
Pairs of forces operate in the balloon to make the car go	The air pushes on the balloon, so the balloon has to push back with the same amount of force in an opposite direction. When the balloon is open, the air can get out, so the part of the balloon opposite the opening doesn't have a resistance on the other side. There is still some air pushing on that part of the balloon, which is the force that pushes the car in the direction opposite that of the escaping air.
Technological Law (in three parts)	
Area of balloon opposite the straw pushes the car	The air pushing on the inside of the balloon, on an area the size of the straw's opening and directly opposite of it, provides the force that makes the car go.
More area opposite the straw gives more area to "push"	If you have more area of balloon opposite the straw where the air is pushing, then you will have more space where that push is happening.
More force = more distance	More force gives your car more distance.

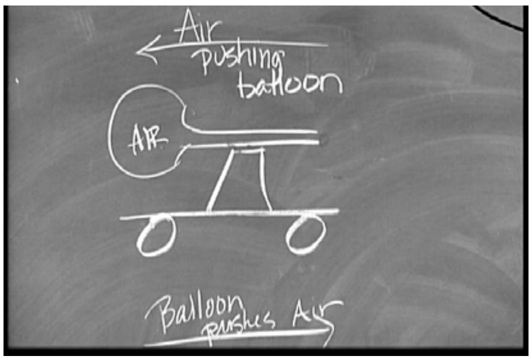
Getting students to "see" the abstract forces operating in the concrete context of the balloon car, a unique way in which engineering design employs science knowledge, was challenging. Ms. Harding acknowledged her own difficulties in understanding and communicating an explanation for the balloon engine:

> I "get" the balloon. But it took me awhile…. I had to stew on it awhile, and it was one of those things that I got myself but I couldn't explain to kids for a long time, because I thought, okay, I get the basic thing, but how am I going to turn around and explain this to 14-year olds. (Retrospective Interview)

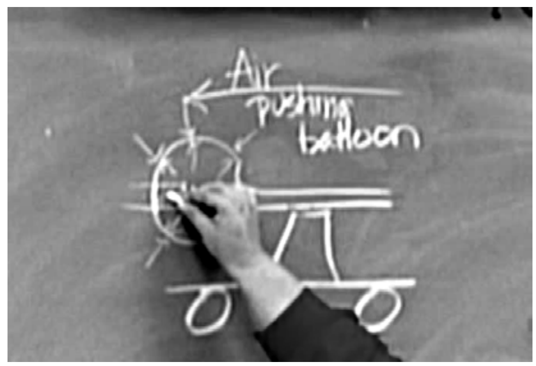
Ms. Harding tried two different approaches to facilitate her students' understanding. She began by having students identify the pairs of forces in the balloon car engine, using a drawing she made on the board of the balloon car, shown in Figure 5a:

> Ms. Harding: Okay my finger's here ((places finger over opening of balloon in the drawing)) and nothing can get out, what's going on?
>
> Student: The air is pushing-
>
> Another student: And the balloon's pushing back.
>
> …
>
> Ms. Harding: Right, if the air pushes on the balloon, the balloon has to push back with the same amount of force in an opposite direction. So when I let my finger go ((removes finger from drawing)), what happens?
>
> Student: All the air comes out.
>
> Ms. Harding: Yeah, the air found a way to escape, right? And so it comes out, and the air travels in this direction ((waves hand to right)) because the balloon pushes the air, right? In that direction ((gestures to right)).
>
> Ms. Harding: … Now you told me that something else is going on. If there's air, something's pushing in this direction ((draws arrow on board to left)).
>
> Several students: [Air] [Air pushing back] [Air].
>
> Ms. Harding: Okay, you've got the air pushing on the balloon in this direction ((indicates left-pointing arrow)).
>
> Ms. Harding: … You guys yesterday identified some different variables that were affecting how your car performed. What do you see here that might make the performance of your car change?

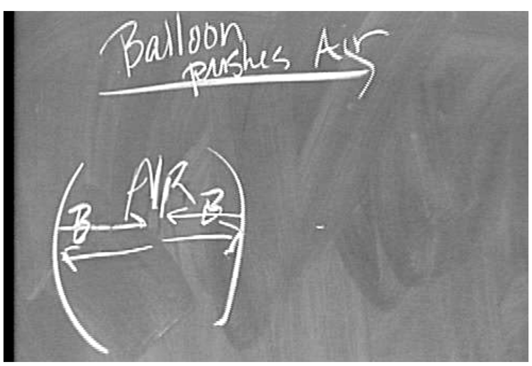
With her final question, Ms. Harding solicited technological knowledge from the students, asking them to apply their understanding of forces in pairs in the balloon engine to features of balloon car design that might affect its performance. Ms. Harding was not satisfied with students' responses, which did not identify the force of air inside the balloon as the force of propulsion, so she tried a second approach, saying "Okay, um, we need to look at the anatomy of this a little bit more care-, uh a little bit more carefully."



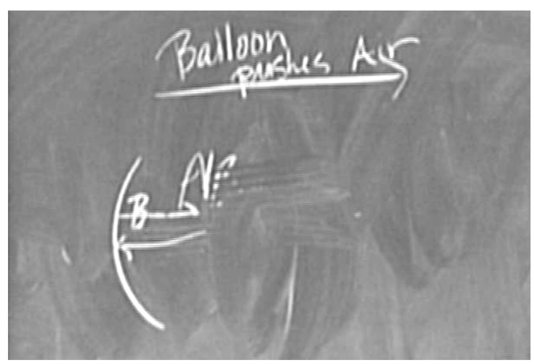
(a) Balloon car system with pair of forces of air on balloon and balloon on air.



(b) Balloon car system with forces of air on balloon and balloon on air drawn around the balloon.



(c) Balloon walls of closed balloon, with arrows for balanced pairs of forces of balloon on air (b1 & b2) and air on balloon (a1 & a2).



(d) Balloon wall of open balloon, with arrows for unbalanced forces of balloon on air (b1) and air on balloon (a1).

Figure 5. *Sequence of drawings the teacher used to communicate a consensus model for pairs of forces operating in the balloon that propelled the balloon car*. Adapted from "Tensions and tradeoffs in a 'design for science' classroom: The 'forces in balloon' lecture," by M. J. Leonard and S. J. Derry, 2006, *Proceedings of the 7th International Conference of the Learning Sciences, USA, 7*, p. 413. Copyright 2006 by the International Society of the Learning Sciences, Inc. Reprinted with permission.

Ms. Harding then explained forces acting on the balloon car at successive levels of abstraction (Figure 5b), until she isolated the balanced pairs of Newton's Third Law forces inside the closed balloon (Figure 5c). Drawing arcs to represent the opposite sides of the closed balloon, Ms. Harding explained,

> 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 and a2)). The balloon is pushing back…. The balloon is pushing this direction ((draws arrows pointing in from each arc, b1 and b2)).

Continuing her explanation, she erased the right arc and said that if it disappeared, so would arrows b2 and a2 (Figure 5d). She explained,

> So that whole side is gone ((indicates right side)), right? So then just this bit ((draws two lines indicating part of the 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)). But the only part that changed is here ((points to place where right arc was erased)). The rest of the balloon is all still there everywhere else, right? So you have this opposite sides working with each other. So when that goes ((pointing to place where right arc was erased)), I still have some pushing against my balloon here ((points to remaining arc where arrow a1 intersects it)).

This was the critical piece of the explanation of how the forces in the balloon propelled the car—Ms. Harding alluded to balanced and unbalanced forces playing a key role (without using those terms). She focused students' attention on the area of the balloon directly opposite the straw, where the Newton's Third Law pair of forces were portrayed as being unbalanced after the balloon was opened. Notably, because of the nature of the activity as design, she attempted to immediately translate forces in the balloon into a technological law for balloon car design, which we discuss next.

The technological law. Ms. Harding's next statement delivered the first piece of her technological law (Table 2), narrowing in on the area on the balloon where she explained propulsion was produced: "It's this little part opposite your straw that affects it. If you look up here ((points to area opposite straw, Figure 5b)), this little bit opposite is all that's affecting what goes out." Ms. Harding subsequently elaborated this law, saying, "So if you can have more area here ((taps the area opposite the straw, Figure 5b)), then you have more space where that push is happening." In summarizing subsequent demonstrations in which students pushed against the wall while sitting on scooter cars, the teacher delivered the final piece of the technological law: "when [Rebecca] pushed harder, you saw her go farther…. So more force is going to give you more distance?" This last piece of the technological law drew on an additional science concept, from kinematics, to link *force* to the design criterion of *distance*.

In sum, Ms. Harding's technological law said maximizing the area of the balloon directly opposite the straw would result in more force, making the car go farther. This law was a logical conclusion from reducing the operative forces to those acting on an area opposite the straw, but it was not accurate in terms of the science and engineering behind the balloon car's propulsion, nor would it explain all the variables in the balloon engine design. The teacher admittedly had a difficult time coming to grips with this explanation herself:

> I got to the point where I "got" where things were going on. It's just that idea that you have these little opposites, so when you increase this diameter here ((referring to the straw's opening)), then you increase what's opposite, the air's forced out, more of it's affected. And so you get, that's just hard. It doesn't make sense, but, but it's this idea that they're two different entities. And when you give one an escape, and there's force on it, as a push here, it goes that way ((out the straw)). But it's still pushing here too ((on the front of the balloon)), because there's some still in the balloon. Until the balloon's empty, it's still pushing right here, because there's still some in there. (Retrospective Interview).

Ms. Harding's technological law represents a tension in translating the science concepts of forces in pairs and unbalanced forces into a technological law. The teacher materials (GTRC, 2004) did not provide a technological law, nor did it provide a science explanation for the effects of changing selected variables in the balloon engine; the teacher attempted to fill these gaps.

Critically, the key to coming up with a productive technological law for balloon car designs was to conceptualize the air inside the balloon not as one entity, but as a quantity of individual molecules. Essentially, each molecule in the balloon was under pressure, or experiencing a force (Force = Pressure x Area). When the balloon was opened, the force that pushed the balloon car forward (due to Newton's Third Law) would be equal to the sum of the forces on each air molecule as it was expelled out the back of the balloon. This, what we call the "molecular-level consensus model," leads to a more accurate technological law: *"More air (or more air pressure) in the balloon will result in more total force on the balloon car and more distance."*

The molecular-level consensus model and the technological law derived from it provide different explanations for balloon engine variables and predict different experimental results than did the curriculum consensus model and the teacher's technological law. For example, the most logical design implication of the teacher's technological law would be to increase the diameter of the straw in the balloon engine to maximize the area of the balloon opposite it. Yet while using a larger diameter straw would give a larger instantaneous force, due to the sum of the forces on the air molecules leaving at the same time, its total force would not increase if the balloon was blown up to a controlled size, therefore neither would its distance (although frictional effects could complicate the results).

Transformations suggested by tensions in teacher's models and modeling. Just understanding and explaining the science behind balloon car propulsion was complex; translating that understanding into a technological law for optimizing balloon car design complicated it further. The struggles Ms. Harding faced indicated ways the curriculum might be transformed to better support the teacher's science and engineering content knowledge and pedagogical content knowledge (Shulman, 1986, 1987), differentiating between Newton's Third Law pairs of forces and balanced pairs of forces, reconceptualizing the air as molecules instead of as one object; and providing a set of technological laws in the curriculum materials that derive from the science and can explain the typical balloon-engine variables students experiment with to optimize their car designs.

Part II: Students' Expressed Models

We preface the results of students' expressed models with details of our analysis of an episode in Group 1's pre-lecture work during Experiment I (see Figure 2 and Appendix A), for the purpose of illustrating how models were derived through an iterative process of coding, discussion, and reflection. We will then present our results and discussion of students' pre- and post-lecture expressed models.

Description of the example episode. The example episode, described in Figure 6 (following page 47), represents part of Group 1's controlled experiments to test their assigned variable: "straw taped on top of cup versus on the chassis." In this episode, Will, Hannah, and Stephanie conducted their second experimental trial with the straw taped on the chassis. To illustrate the logic of how codes were assigned to units of Discourse in this example, the coding categories are italicized in the explanation that follows.

The episode began with the group measuring the balloon, Hannah reminding them they had to *control* (as a *variable*) its size at 75 centimeters in circumference (lines 950-954, in Figure 6). When Stephanie positioned the balloon engine on the chassis, readying it to be taped in place (lines 955-956), Hannah said they had it facing the other direction before (line 957) but Stephanie kept it the direction she had it (line 959), effectively *abandoning control* of which end was the front versus the back of the chassis (a *variable*). Hannah reminded the group they had to measure the distance from the edge of the chassis to the opening of the balloon (lines 958-973), another *variable* they were *controlling*. Next, Will made an *ordinary prediction* that the car was not going to work (line 978); it was classified as ordinary because there was no evidence he based it on a scientific theory, but rather on results of previous experience.

At the same time, Hannah predicted the car was going to move in the direction opposite what they intended and in the same direction as the expelled air (line 979), expressing her (incorrect) *operational principle* for the car. Stephanie stated that the reason the car did not move in a previous trial was because the balloon hit the ground (line 980), which was a *weak causal explanation* in that it linked an action (the balloon hit the ground) and reaction (the car did not move) but stopped short of identifying an underlying (and often, unseen) mechanism accounting for why the action caused the reaction. In other instances, students named friction as the underlying mechanism that prevented the car from moving when the balloon hit the ground; identifying friction would have made Stephanie's explanation a *strong causal* one. The explanation Stephanie gave (in line 980), along with the *descriptive explanations* that followed (lines 982-983), also communicated *structural* (technological) knowledge, illustrating how the scientific and technological coding schemes could overlap in the Discourse.

Finally, when the air left the balloon without the car moving, Hannah exclaimed that the air released from the balloon was just going down the chassis, which would not make the car move (line 985). Based on a study of the Discourse, including Discourse beyond this example, we coded her statement as a *strong causal explanation*. We believe she was struggling with identifying an underlying mechanism of balloon car propulsion to explain what was happening, even though the mechanism she identified was not scientifically correct.

Models of balloon car motion expressed in the example episode. The Discourse example illustrates three primary models of balloon car motion, expressed in a mix of scientific explanations, technological knowledge, and actions on variables (the Analysis of Student Models section describes how model categories were inductively derived from Discourse across the whole activity). Hannah expressed the first model in her strong causal explanation at the end of the episode (line 985). She asserted the air leaving the straw and just moving down the chassis was not going to make the car move, implying that the causal mechanism for balloon car motion was the air interacting with something after it left the balloon. We termed this the *interaction of expelled air* model. This model (although scientifically inaccurate) was commonly expressed by students in the pre-lecture phase. Strong causal explanations like the one Hannah gave were especially important in our analysis because they were the type of explanation curriculum developers and the teacher were working to get students to make—identifying and understanding scientific mechanisms that accounted for their car's performance. Strong causal explanations easily translated into models of balloon car motion.

Stephanie expressed the second model in an utterance that was coded as both a weak causal explanation and technological knowledge (line 980). Her explanation that the balloon hitting the ground stopped the car from moving was classified as an *interference* model, which identified a structural issue affecting a car's motion. This model, too, was commonly expressed in the activity, especially during the early sessions when students struggled to get their cars to move at all. Interference models were expressed in ideas and operations across the Discourse representing a range of codes, including weak causal explanations, structural ideas, ordinary predictions, descriptive explanations, and setting a variable to test it. It is noteworthy because it illustrates how the nature of this activity as design-based science resulted in a mix of technological and science explanations, not just scientific ones.

The third model in the Discourse example was expressed in a variable the group chose to control during their experiment, the amount of air in the balloon (lines 950-954). Variables indicated factors students thought could affect the motion of their car. We interpreted the group's attention to the amount of air in the balloon as an expression of the *more/larger is better* model that students at other times stated explicitly as "more air in the balloon makes the car go farther." Variables sometimes contributed directly to identification of expressed models. Other times, the underlying models that may have guided students as they selected or released variables were not as clearly indicated, such as front versus back of the car (lines 957-959), or distance from the edge of the chassis (lines 958-973). In such cases, students' operations with variables were not interpreted in our analysis as communicating models of balloon car motion.

Students' pre-lecture expressed models. Prior to the Force Lecture, the models students expressed most frequently were focused on structural issues that either created interference with the balloon or improved the car's performance, and on qualities of the air leaving the balloon. Table 3 identifies students' pre-lecture expressed models[1]; we discuss the most important models and tensions they revealed.

Table 3

Types and Frequencies of Models of Balloon Car Motion Students Expressed during Pre- and Post-Lecture Sub-Activities

	Frequency of Expression	
Model	Pre-lecture	Post-lecture
Interference	33	3
Qualities of air leaving balloon	24	11
Interaction of expelled air	22	0
More/bigger is better	15	1
Prior knowledge (including friction)	14	3
Force	5	26

Interference. The most frequently expressed pre-lecture model attributed balloon car performance to interference from the balloon hitting the floor or the wheels of the car. Interference models were primarily revealed in small-group sub-activities as students worked through alternate design configurations for their cars. During Messing About, for example, Group 1 quickly became caught up in a quest to keep the balloon from touching the floor or the wheels. The group tried a series of structural changes to eliminate this problem, first elevating the engine by attaching it higher on the cup, then using the bendable straw, and, later, setting the straw at an angle relative to horizontal with the balloon higher than the straw.

Group 1 made more references to interference throughout the pre-lecture phase than any other single factor. This reflects a tension in the activity system, between the object of getting their cars to run and the projected outcome of explaining the science behind the car (Figure 1). Students offered very few strong causal (scientific) explanations for the cars' performance in the pre-lecture phase. Early in the design activity, the immediate challenge students were trying to solve was getting their car to move under balloon power, which led to a focus on structural (technological) issues such as interference.

[1] The models reported here derived from both technological and scientific ideas and operations (see description of the example episode).

Qualities of air leaving balloon. The balloon was obviously the source of propulsion for the car, and students often attempted to explain their cars' performance in terms of qualities of the air leaving the balloon (e.g., how much came out, how fast it came out). In discussions surrounding their presentations of experimental results during Poster I, for example, members of Group 4 attributed their car's performance to the *amount and speed of air* coming out of the balloon:

> Will (Group 1): How did you determine which straws to use?
>
> Marshall (Group 4): Um, we were wanting to make it go, go further, go the furthest, so we decided to use the biggest straw. Using the biggest straw because it blows out more air and faster means it'll push, make it go further. So we used that straw.

In Group 1's investigations during Messing About, Will also named *speed of the air coming out* of the balloon as a factor in the car's performance. Stephanie wanted the group to try a bendable straw for their balloon car engine, which would raise the balloon off the wheels. Will protested using it, saying "but it, the air doesn't come out as fast if it's bendable."

Interaction of expelled air. Expressions that identified the underlying mechanism for balloon car motion as the interaction of the air after it had left the balloon car system were abundant across the pre-lecture Discourse. The Discourse example (Figure 6) illustrated one instance, in Hannah's exclamation at the end that the car was not moving because the air was just going down the chassis. In another example, students expressed concern about the reliability of Group 3's experimental results when they tested the position of the cup on the chassis: front, middle, or back. The group had set their engine at an angle, with the balloon higher than the straw, and students were concerned that having it at an angle changed what the air was blowing on. In Poster I, Brandon explained why their group angled the straw:

> I thought like, if the air was pushing against the um, like when [the cup holding the engine is] on the, back, if it's pushing against the, the floor instead of the chassis it'd go farther instead of pushing against itself.

When the teacher asked the class what they thought about the straw's angle, several students expressed concerns about controlling what the expelled air interacted with.

Ms. Harding had a name for this (mis)conception: the Magic Air Syndrome. She identified it as one commonly held by students in her classes. "They think that if, the, that the air that's coming out at the end of the straw, the exhaust, affects how their car goes forward" (Retrospective Interview). It was the most frequent model students expressed during the Lecture Prelude when they were asked to discuss how the balloon made the car go. (This model was not limited to students, either; it was a common conception expressed by educational researchers during one of the interaction analyses held on this study's video data.)

More/bigger is better. The more/bigger is better model attributed better balloon car performance to having more engines, more air in the balloon, or a larger diameter straw. The most frequent version of this model was *more air in balloon* (eight expressions). During Messing About, for example, Stephanie alluded to the size of the balloon as the reason why the car did not work, saying to Will, "I think it's cuz [Hannah] can't, she doesn't blow up the balloon very far." Later, Will communicated this to the class (during Sharing Observations), explaining,

> Like the more air that you put into the balloon makes it go farther, like when Hannah blew it up, she didn't blow it very big and didn't go as far. If we blew it up like real big, goes farther.

This model appeared sometimes to be intuitive, a possible p-prim (diSessa, 1988, 1993), and other times to be generalized from empirical results as a technological law (Ropohl, 1997). In either case, it represented a tension, as students quickly established it as a design principle, one that was (unbeknownst to them) consistent with the molecular-level consensus model of balloon car propulsion, but one that was not acknowledged or incorporated into the curriculum consensus model or the teacher's technological law that students later received.

Another version of the more/bigger is better model, *larger diameter straw is better*, foreshadowed the technological law the teacher would deliver during the lecture. When they shared their early observations, students noted that "the larger the diameter [of the straw], the better it went," and that while smaller diameter straws worked, "they just got a slow start." Marshall explained Group 4's design decision in these terms:

> We were wanting to make it go, go further, go the furthest, so we decided to use the biggest straw. Using the biggest straw because it blows out more air and faster means it'll push, make it go further. So we used that straw.

Friction[2] (prior knowledge). In some instances, students took their explanations of interference further, to identify an underlying mechanism of friction. These explanations appeared to apply students' prior knowledge from the preceding coaster car activity. Students occasionally made the connection to friction spontaneously, as when Hannah discussed the issue of the balloon touching the wheels during Messing About, "It's still touching.… That's a problem. It makes it slow down. It means friction." Most of the connections to friction came during Poster I, and, in Group 1's case, Ms. Harding facilitated the group in explaining "collisions" between the balloon and the wheels or floor in terms of friction, then summarized by saying, "So, it's not good enough just to tell me it doesn't collide. You, when you know the

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[2] In Physics and the ViM curriculum, friction is a force. However, in the enacted balloon car activity system, references to friction were usually made without distinguishing it as a force; it was referred to simply as "friction," rather than the "force of friction." Furthermore, the curriculum consensus model and teacher's technological law did not include the force of friction as part of the explanation for balloon car propulsion. Therefore, we use the classroom convention in referring to friction as a model and concept apart from that of force.

science behind it I want to hear the science behind it. And you know this. We all know about friction."

Yet there were tensions in the activity regarding friction. When the class selected the variables to test for Experiment I, Ms. Harding expressed her dissatisfaction with their selection of a predominance of what she called "fabrication" variables (e.g., placement of the cup on the front, middle, or back of chassis; straw taped on top of cup versus on chassis). Because the focus of the balloon car activity was on forces in the balloon, the teacher wanted "them testing things that have to do with balloons and straws" (Retrospective Interview) (e.g., number of engines, diameter of straw). Our Discourse analysis, however, revealed these fabrication variables were related to friction. The tensions arose in: (a) not recognizing "fabrication" variables as related to friction and relevant to the net force on the car, (b) the role of friction in science versus engineering—science often assumes a frictionless system in solving its problems, while engineering explicitly works with friction problems in designing solutions, and (c) the object of designing a balloon car versus the projected outcome of learning about forces in pairs (Figure 1).

Force. Students made few references to forces in their pre-lecture Discourse. Two occurrences of force models were a statement and example of Newton's Third Law of Motion, triggered by the teacher's analogy of the balloon car to a rocket. Yet the group could not further explain these.

> Ms. Harding: How does a rocket work, work in space?
>
> …
>
> Tony: Oh, Newton's Third Law!
>
> Ms. Harding: What's Newton's Third Law?
>
> Tony: For every, action there's an equal but opposite reaction. Something like that.
>
> Ms. Harding: What does that mean, in terms of how a rocket works?
>
> Tony: I don't know! ((Laughing))
>
> Danny: If you're pushing against the wall, the wall's pushing against you.
>
> Tony: I know, I just–
>
> Ms. Harding: So, then, what makes a rocket go in space? If they want to speed up slow down turn, in space, what do they do?
>
> Jeff: I don't know, they just (affect) the propulsion.

At times in the pre-lecture Discourse, students flirted with ideas of force, speaking of "thrust," "power," and "energy," terms students have been found to conflate with force (e.g., Hestenes, Wells, & Swackhamer, 1992; Leonard, Rebello, & Puntambekar, 2007). For example, during their first Poster Presentation, members of Group 4 told the class they thought putting four engines on their car would work better because "the more the better." When the teacher asked them why they thought that, the group replied:

Ryan: More power.

Marshall: Has more power.

Ms. Harding: How does it have more power?

Narend: More air getting released.

Marshall: More air getting released out of 4 engines rather than 1. Just like having 4–

Narend: 4 times the power.

Students' pre-lecture force models appeared vague, undeveloped, and intuitive; they discussed balloon car performance almost exclusively in terms of concepts other than forces as they worked on viable initial designs for their cars.

Transformations suggested by tensions in students' pre-lecture models. The design context added complexity to an activity whose primary goal was getting students to understand the forces that propelled their cars. Students' struggles designing their cars in the pre-lecture phase revealed their thinking about balloon car propulsion, but did so primarily in terms of models related to technological, not science issues. Students rarely mentioned forces. As a result, Ms. Harding had already transformed the activity, adding the Force Lecture to try to get them thinking in those terms. Yet the types of models students expressed before the lecture and the tensions we identified suggest additional ways in which the activity may be transformed to better balance its design and science goals and knowledge, as follows.

One transformation is suggested by the mismatch between what preoccupied students during the pre-lecture phase (getting their cars to run) and what the teacher wanted them to focus on (forces in the balloon). This tension reflects what Kimbell, Stables, and Green (1996) described as the product purpose versus the learning purpose of a design task. Kimbell et al. asserted that every project requires both kinds of outcomes, and the balloon car activity complied—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). However, it is important for curriculum developers and teachers to recognize that there is an inherent tension between these purposes and that an acceptable balance must be achieved. This means, for example, that fabrication (or friction) variables will be present in a design activity—they may either be embraced as part of the product (engineering) purpose of the task or downplayed in order to give more time to the learning (science) purpose of the task. Ms. Harding took the latter approach, reporting that in subsequent years, she transformed the activity further by rescheduling the Force Lecture to immediately follow Messing About and precede Selecting Variables, which allowed her to more strongly steer students toward issues "that deal with force, everything to do with the engine" (Retrospective Interview) and away from friction or fabrication variables.

A second transformation is suggested by the tension between the models students expressed in their explanations and the technological law the teacher provided. Constructivist theories identify the importance of students' existing ideas in developing science understandings, and the pre-lecture phase revealed many opportunities for building on their ideas (also see Leonard & Derry, 2007). For example, students' ideas about the effects of the amount of air in the balloon could provide an entrée to the molecular-level consensus model. The first step in successfully building on that understanding would be developing the teacher's own conceptual knowledge to embrace a more detailed consensus model and a more accurate technological law. A second step would be assisting the teacher in recognizing how students' intuitive or empirical ideas about balloon car motion relate to the targeted consensus model and technological law, developing her pedagogical content knowledge about students' thinking and conceptual pathways in learning about forces (Steedle & Shavelson, 2009; Scott, Asoko, & Driver, 1991). A final step would be assisting the teacher in developing a more sophisticated understanding of engineering design and its complex relationship to science.

Students' post-lecture expressed models. When we examined students' post-lecture expressed models (Table 3), we found a large number and range of models that appropriated ideas of forces, almost to the exclusion of any other model except for qualities of the air leaving balloon, which was still frequently expressed.

In this section we will discuss the post-lecture models. Before we do, however, it is important to note that in addition to the curriculum consensus model and teaching models she delivered in the lecture, Ms. Harding gave students additional requirements for their second Poster Presentations, which affected the Discourse. For Poster II, groups were to include a *motion storyboard* (described in Table 2) for each variable setting, as well as a *rule of thumb* for balloon car design that was based on the science. One of the curriculum developers considered these tools "our two sort of key curriculum elements; they are practices, say, or moments that allow students to make connections between abstract science content and learning and the context they are working in" (Interview 55A). The design rule of thumb prompted students to explicitly link their car designs to the science (Ryan et al., 2001). They functioned as design recommendations or *functional rules* (Ropohl, 1997) that ideally took the following form:

> **When** *(describe the action, design, or choice you are working with),*
> **use/connect/build/employ/measure** *(list your suggestion or method),*
> **because** *(list or supply the science principle or concept here that backs up your suggestion)* (Ryan et al., 2001, p. 3).

Interference. In the post-lecture phase, *internal (to the balloon-car)* interference was not mentioned at all in student Discourse (whereas it was dominant in pre-lecture Discourse). Students' structural knowledge grew as they figured out ways to keep the balloon from hitting the wheels, the ground, or other balloons; as their knowledge grew, issues with interference were no longer present. The only interference models expressed in the post-lecture Discourse came when the spring scale Group 1used to measure the force on the car interfered with its motion, creating *external* interference.

Qualities of air leaving balloon. Students continued to attribute balloon car performance to the amount, speed, duration, or restriction of air leaving the balloon (however, the overall frequency of these explanations decreased by half). A new feature of air believed to affect performance was added during Experiment II when Will attributed the straightness of the car's path to the *steadiness* of air coming out of the balloon.

Of the qualities of air affecting performance, the s*peed of air* leaving the balloon was the most often expressed. In one example, members of Group 5 tested effects of the size of the balloon's opening, which they varied by bundling multiple straws together to effectively create one straw with a larger diameter. Nicole attributed their car's performance to the speed of the air leaving the balloon:

> Our recommendation, or our rule of thumb is that, because the um, passageway is larger and air can leave the balloon faster, the car with 3 straws will work the best, so you should put 3 straws per engine, on your car.

This example is noteworthy for a couple of reasons. First, it represents a tension between students' intuitive ideas and the models and law the teacher provided. The diameter of the straw was the variable most directly related to the teacher's technological law, but Group 5 did not use it in its explanation. Instead, members of the group appeared to focus on their direct observations, naming the speed of air as the operative mechanism, rather than explaining the straw's effects in terms of unseen, and inferred, forces. Second, Group 5's experimental results did not quite support its rule of thumb. Their data showed the 3-straw engine did have the largest *initial velocity*, but it tied with the 1-straw engine for *distance,* and both traveled further than the 2-straw engine. Students may have based their rule of thumb on what they thought should happen, rather than what actually happened in their experiments (Chinn & Brewer, 1998). Or perhaps the connection between speed of air and speed of car was more salient to them. In the end, their rule of thumb was supported by the car's initial velocity but not by distance, the design criterion they were trying to meet.

Although the frequency of the *quality of the air leaving the balloon* model decreased, the fact that it remained as high as it did indicates students continued to view this feature as instrumental in balloon car performance.

Interaction of expelled air. After the Force Lecture, we did not detect any expressions of the *interaction of expelled air* model for balloon car motion, suggesting that the lecture possibly redirected attention to the Newton's Third Law explanation of forces inside the balloon. As mentioned earlier, Ms. Harding recognized the lecture's potential for cutting down on conceptions such as the "Magic Air;" since the implementation we studied, she has scheduled the lecture even earlier, before the first round of experiments, to redirect students' thinking about the causal mechanism early in the activity (Retrospective Interview). While the lecture did appear to be successful in this regard, the handling of this student (mis)conception represents a tension between the instructional approach taken and an inquiry approach to developing science understanding. Contemporary science education theory, standards, and practice call for students to develop their own explanations for phenomena they observe (NRC, 2000). When (mis)conceptions such as *interaction of expelled air* are involved, teaching for conceptual change strategies encourage students to test their ideas through science investigations (e.g., Guzetti et al., 1993). Using a lecture to teach the science behind balloon cars, it could be argued, may not have developed students' scientific understanding of balloon car propulsion as deeply or robustly as engaging them in inquiry had the potential to do.

Delivering the curriculum consensus model and teacher's technological law in a lecture reveals another tension in achieving both the object of designing a car and the projected outcome of understanding the science behind it (Figure 1) within the finite time available for the activity in the classroom (Leonard & Derry, 2006). Designing a balloon car was intended to facilitate understanding of the science, but it actually may have limited the time available for students to develop their science understandings through inquiry.

More/bigger is better. Models based on the idea that more/bigger is better virtually disappeared from the Discourse in the post-lecture phase, indicating that students may have found other ways to express their ideas in terms of forces. Notably, the sole expression of this model was in reference to the *amount of air in the balloon*, which was consistent with the molecular-level consensus model and related technological law proposed earlier, and indicates the strength of this (accurate) student conception.

Friction (prior knowledge). As students' structural knowledge grew, they eliminated sources of unwanted friction in their cars, and this model all but disappeared in the post-lecture Discourse. One case where this model appeared was during Group 3's presentation of its experimental results for the length of straw. Brandon gave the group's explanation and rule of thumb, "[W]hen the air is pushed, of, out of the balloon, through the straw, friction builds up.... So our rule of thumb is to use a shorter straw, to reduce friction, and allow the car to go farther." During their Poster Presentation, members of Group 3 alluded to consulting the teacher on their conclusion, but Ms. Harding herself was not sure what the causal mechanism was for this variable:

> The straw length is a weird one anyway. I haven't yet gotten a great explanation on that. I have my theories, but I don't know that I know enough to really say this is true on the straw length but, but I know that we consistently see the same things on the straw length (Retrospective Interview).

The difficulty explaining why a shorter straw resulted in more distance represents a tension in the activity. The curriculum consensus model and technological law students received did not account for this variable. An explanation can be derived from the molecular-level consensus model: Air molecules leaving the balloon were slowed by friction as they passed through the straw.

Force. Following the lecture, students across the board appropriated the language of forces into their explanations of balloon car motion, albeit with varying degrees of alignment with the curriculum consensus model and teaching models. Full connections to the teacher's expression of the curriculum consensus model, that the *air pushing on the back of the balloon* was responsible for the car's propulsion (Table 2), were made only when Ms. Harding coached Hannah in preparing her poster and later when Hannah elaborated on her group's rule of thumb recommendation during Poster II:

> Will: And, we recommend that you use three layers of balloons, so the force pushing out, is larger, so therefore it'll go farther.
>
> Hannah: Um, and that works because the reason, that your car goes is because, the um, back of, it's the air pushing on the back of the balloon. And so if there's more layers, then the, back of the balloon is pushing harder, so therefore the air has to push harder on it, because force works in pairs. And once there is an opening, the force of the air that would be pushing on it goes out. The hole. And makes it go farther.

In her explanation, Hannah invoked both the curriculum consensus model and the teacher's technological law to explain how double-ballooning (placing one balloon inside a second one and gluing the double balloon to a straw) worked. The model and law were plausible but inaccurate, representing a tension in the activity regarding the adequacy of the models and law for explaining the variables students tested. Accurately explaining why double-ballooning propelled the car further required the molecular-level consensus model, knowing that air is made of molecules. According to Newton's Third Law, each molecule of air in the balloon experienced a force exerted by the balloon; correspondingly, each molecule of air exerted an equal and opposite force on the balloon. Thus, the best way to maximize the force on the balloon (and the car to which it is attached) was to increase the number of air molecules inside the balloon. Blowing the double balloon up to the same size as the single balloon, a variable students controlled, kept the *volume of the balloon* the same, but the *number of air molecules* increased because the air was compressed more due to the increased pressure of the double balloon. Controlling and measuring the amount of air put into the single versus double balloon, rather than the balloon's inflated size, would have enabled students to observe this key difference.

Other models in post-lecture Discourse picked up elements of the teaching models: *forces in pairs*, which also arose in Ms. Harding's coaching session with Hannah, and *no acceleration*, expressed by Nicole in discussing Group 5's motion storyboard, as follows.

> The force net in the beginning was zero, because um, if the balloon is filled and the air is pushing on the balloon, but if you're um, closing up the air hole, then it's pushing the same amount on the hole as it is on the balloon, because the car isn't moving.

The majority of the force models students expressed contained elements of the curriculum consensus model and teaching models but did not incorporate all elements of the full model. A number of expressions attended to one side of the interaction equation but left the other unspecified, i.e., forces *on the balloon* or *of the air* but not both. Closely related to these was the *net force model*, which students often expressed in describing their motion storyboards in Poster II, where free-body diagrams of the car included a "force of air" vector. Throughout post-lecture Discourse, students spoke of "the force of air" without naming the other side of the interaction. And similar to what other researchers have described (e.g., Watts, 1983), students' expressed models did not always reflect an understanding of forces as *exerted by* an object. One expression stated it as force *released* from the engine, drawing a parallel to the air released from the balloon; another stated force as being *with* an engine, as if a property of the object.

This situation raises several issues in interpreting the classroom Discourse. The partial uptake of the scientific discourse of forces indicates students were attempting to incorporate it into their reasoning about the balloon car (Alonzo, 2010). This is a productive step for students, as teachers can leverage this nascent understanding into more expert understanding (Wertsch & Kazak, 2011). However, Wertsch and Kazak warn this phenomenon makes it difficult to assess how much students truly know, as students may begin using language without fully understanding its meaning. Students may have been merely exhibiting awareness and compliance with social norms and conventions in the classroom, rather than exhibiting a deep commitment to the explanatory power of the models and law (P. Hewson, personal communication, 6/18/2006). Students had been directed to present their experimental results in terms of design rules of thumb linking their designs to the science, and to explain their cars' performance in terms of the teacher's models and law of forces in the balloon. They may have been primarily responding to the teacher's directions rather than expressing understanding or acceptance of the explanations they received. Wertsch and Kazak (2011) recommend being conservative in interpreting students' understanding of the scientific discourse they are beginning to use. Yet students' force models give us insight into the aspects of science and technological models that were more readily appropriated, providing insight into students' learning progressions that can be supported by curricula.

Transformations suggested by students' post-lecture expressed models. Cognitive science and conceptual change literatures tell us developing students' conceptual models requires starting from students' existing ideas and understandings. diSessa (2006) recommended that "instead of rejecting student conceptions, one can pick and choose the most productive student ideas, and refine them to create normative concepts" (p. 266). Across the balloon car activity, students expressed models that provided good foundations upon which to build more scientific understandings: their lasting interest in how the amount of air in the balloon and qualities of the air leaving the balloon affected propulsion, reoccurring concern about friction, and naïve ideas about force. Starting from and working with their ideas in the activity gives students something to connect to in developing their conceptual frameworks about force and motion as well as requiring them to identify and evaluate their existing conceptions (Hewson, Beeth, & Thorley, 1998).

The balloon-car activity focused on *design*, but incorporating time and space for students to conduct *inquiry* into the science behind their designs might have improved their understanding of how forces propelled their balloon cars. As discussed in the theoretical framework, engineers sometimes use experiments in an engineering role to test designs, other times in a science role to understand the relation between cause and effect. By incorporating science experiments, students could test their ideas about the operative factors in balloon car propulsion, for example, measuring the speed of air leaving the balloon and comparing it to total distance the car traveled.

The teacher's technological law was not accurate in explaining balloon car motion nor was it sufficient; the curriculum must provide these critical links between the science and designs. The molecular-level consensus model more accurately accounted for double-ballooning and multiple engines and better predicted the results of increasing the size of the balloon's opening through bundled or larger-diameter straws. However, to explain how the length of straw affected balloon car motion, students additionally needed a law about the force of friction on air being proportional to straw length, based on the molecular-level consensus model but extended to acknowledge friction and its effect of reducing net force in direction of travel. A design-based science curriculum must acknowledge the need for such higher-level technological knowledge and encourage its development in the activity. In addition to being derived from scientific laws, technological laws can also be developed from empirical experience, and this happened in the balloon-car activity. Group 2, for example, introduced a new technological law during Poster II to explain its experimental results: Putting the straw horizontal worked best because all the force was in the direction you wanted the car to go. Thus technological laws derived from empirical observation can be leveraged to help students understand the science.

Summary of Analysis

Our analysis sought to describe ways in which science and design interacted in the balloon-car activity system. There was evidence that the design activity provided affordances for learning science concepts. It enabled students to manipulate design variables and observe their effects on balloon car propulsion. The Force Lecture, rules of thumb, and motion storyboards resulted in students appropriating the language of forces in explaining their balloon cars' performance—explaining the science behind their designs. However, the design context also presented constraints for science learning. Throughout the activity, we identified tensions within the activity system (Figure 7) that shed light on the particular challenges of using a design context for science learning. We summarize key tensions as they relate to the goals, knowledge, and practices of science versus engineering.

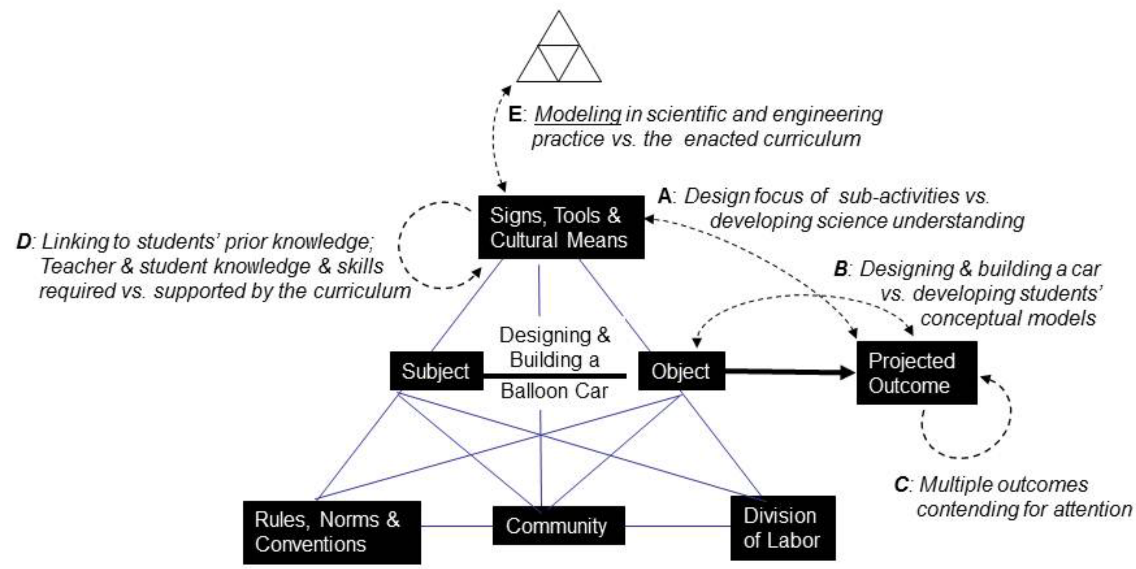

Figure 7. *Tensions in the balloon car activity system. Tensions are identified in italics with dashed lines linking one or more activity system components.*

Goals. A constant tension throughout the activity was designing a balloon car to go as far as possible versus developing an understanding of the science behind the car (A, B, and C in Figure 7), a direct reflection of the different goals of engineering and science. The design context required students to attend to structural issues rather than science concepts in the early sub-activities when their objective was simply getting their cars to run. And it was possible to design a car to meet the specifications without explaining how or why it worked in terms of the "science behind it." Therefore, the curriculum introduced several tools to build a need for the science into the activity, most notably the lecture and the rules of thumb. After 2 weeks of working with balloon cars students were just beginning to talk about forces, and not with complete fidelity. They were, however, successful in getting their cars to go far and straight.

Knowledge. Tensions in science and engineering knowledge arose throughout the activity (D in Figure 7). There were tensions between the knowledge provided by the curriculum, required in the activity, and present in students' and teacher's background knowledge. The balloon car was a complex setting for learning about Newton's Third Law; additional concepts were necessary to explain its propulsion, including those within Newtonian mechanics, kinematics, and the molecular nature of matter. Students expressed intuitive ideas about balloon-car propulsion that could have been leveraged to develop their understanding of the science. At the heart of this tension was the lack of an accurate and complete set of technological laws to connect the cars to the science.

Practices. Models and modeling represented a tension in the enacted curriculum (E in Figure 7). Modeling is inherent to both engineering and scientific practice. It was an epistemological requirement of the balloon-car activity to do modeling; it was equally an implicit requirement in the classroom. Ms. Harding engaged in modeling to express models of balloon car motion to students; she assessed students' understandings through the explanations they gave (Gilbert, Boulter, & Rutherford, 1998a & b). However, there was a tension in that the curriculum did not explicitly identify and support this aspect of doing science and engineering; its focus was on experimentation, the sister of modeling. In professional engineering and science practice, the two processes work together, with conceptual models built from and tested in experimentation. The curriculum team reported that the ViM curriculum (the early version we studied) did a better job developing students' experimentation skills than it did developing their science conceptual knowledge (Kolodner et al., 2003; Interview 55A). The results of our analysis—that students did not fully appropriate the curriculum consensus model or teaching models provided in the lecture—support the curriculum team's assessments. The teacher's struggle in communicating models in the lecture suggests teachers, as well as students, would benefit from additional support in models and modeling (see also Leonard & Derry, 2006).

Conclusion and Implications

This study unpacked details of a design-based science activity, revealing the demands it placed on students and teachers in integrating the goals, knowledge, and practices of science and engineering. While engineering and science are highly interrelated, epistemological differences resulted in tensions in the classroom activity. Learning science in a design-based activity was complicated by the competing goals of designing a product to specification and learning the science in a product-design context. In addition to the targeted science knowledge, the design activity required technological knowledge plus science concepts beyond those targeted for study. Successfully achieving science and engineering goals required the practice of modeling in addition to experimenting.

A central challenge is that engineering design projects are not simple contexts for seeing science in action. These contexts challenge one's understanding of science concepts as they manifest themselves in multiple and nuanced ways. Seldom in a design context does a science concept appear in an isolated form that allows it to be studied discretely—it operates in concert with multiple, intersecting science and technological concepts. Accomplishing a design-based science project requires synthesizing multiple science and technological concepts in order to move from understanding a concept to the more challenging step of applying it in the service of meeting a design goal.

To accommodate the challenges of design-based science, it is necessary to build into the curriculum an understanding of the interaction between goals, knowledge, and practices of science and engineering. We summarize and highlight three specific implications for curriculum development. First, curricula should identify common design variables and provide explanations of the science and engineering concepts that account for an artifact's behavior. Identifying technological laws is critical as they connect the science to the designs. Second, merging design and science requires giving time and attention to achieving learning outcomes in each area. If the activity is intended to provide a context for learning science, sufficient time must be allocated to science inquiry in addition to achieving the product-design goals. Third, incorporating modeling into the activity will not only better represent the practices of science and engineering; our analysis suggests explicit attention to modeling can facilitate better links between the products under design and the science behind them.

Design-based science places unique demands on teachers, and they will require knowledge in several dimensions; key implications for teacher professional development are discussed here. A first implication is that teachers must become aware of the interactional relationship between science and engineering (as distinct but interrelated domains) and how their relationship, similarities, and differences may play out in the design-based science classroom. A second implication requires developing a strong understanding of the subject matter under study, including science conceptual knowledge, technological knowledge, and science and design skills (Kolodner et al., 2003; Schneider, Krajcik, & Blumenfeld, 2005). Especially important is developing the ability to engage in modeling—teachers developing and communicating their understandings of the science behind the design (Leonard & Derry, 2006). Teachers will need robust conceptual models of the phenomenon, not only for effective teaching models, but to assess and foster development of students' conceptual models. Design-based science contexts (like inquiry contexts) challenge teachers' science content knowledge. Because it is impossible to fully anticipate how a teacher's knowledge will be challenged, a third implication is to encourage teachers to enter into the activity as a co-designers (or co-inquirers), removing the pressure to know the "right answers" and allowing teachers to investigate questions and problems with students. This requires rethinking what it means to teach (expanding one's pedagogical knowledge). A final implication for teacher professional development is developing teachers' pedagogical content knowledge (Shulman, 1986, 1987) for design-based contexts. This includes understanding students' common conceptions of the science behind a design and the conceptual pathways students tend to follow once teaching is underway, as well as appropriate teaching strategies to assess and develop students' conceptions in this context.

The challenging nature of design-based science activities creates an exciting context for learning science, but its demands should not be underestimated. In the activity under study, students exhibited some real development in their science knowledge, and, although it was far from what might be hoped, it might be improved significantly with our recommendations for curriculum design and teacher professional development. However, in order to develop realistic expectations of what may be accomplished in these activities, it is necessary to consider the complexities our study uncovered, the knowledge and skill required of teachers and curriculum designers to implement this form of curriculum, and the time required to immerse students in this type of learning.

Line	Hannah	Will	Stephanie	Video Still	Code
950	((Holds measuring tape on balloon.)) Has to be 75 from the center.				
951	That's too big.				Set Controlled Variable
952			Let a little out.		
953		((Lets some air out of balloon.))			
954	[That's good.]		[That's good.]		
955	Kay. Do you have tape?				
956			Yeah, Will's got it. ((Places balloon on car, opposite end from previous test run.))		
957	Wait, here, we put it? ((Gestures to opposite end of car.))				Abandon Controlled Variable
958	[Oh, it has to be 7] centimeters, remember, from the,				
959			[We'll put it here.]		
960		Yeah.			
961	End?				
962		7 centimeters, right? We taped it on 7 centimeters.			

Figure 6. Transcript and coding of example episode from Group 1's small-group work during Experiment I (pre-lectu).

Line	Hannah	Will	Stephanie	Video Still	Code

Line	Hannah	Will	Stephanie	Video Still	Code
963	Yeah, but you have to do it again				
964		((Hands end of measuring tape to Stephanie.))			Set Controlled Variable
965	cuz, we don't know how far it is.				
973	… it's about right [there.]				
974		[Tape on] tape on. There. ((Puts a piece of tape over straw to affix it to chassis.)) Yeah. Do you have it pinched?			
975	Yeah.				
976		Oh. ((Laughs.))			
977	((Sets car down on floor, balloon pointing away.))				
978		This isn't gonna [work.]			Ordinary Prediction

Figure 6 (continued).

Line	Hannah	Will	Stephanie	Video Still	Code
979	[That's] not gonna, it's gonna move this way ((motions toward herself.))				Ordinary Predication; Operational Principle
980			That's cuz the balloon hits the ground.		Weak Causal Explanation; Structural
981	((Students watch the balloon deflate while car remains stationary.))				
982	Yeah? No, not really.				Descriptive Explanation; Structural
983			When it first did.		Descriptive Explanation; Structural
984	((Picks up car.))				
985	Oh I know why! It's too far in! It's not gonna, the air's just going to go here ((moves hand from opening of straw down chassis)). It's not going to make it move.				Strong Causal Explanation

Figure 6 (continued).

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Appendix A

Sub-Activities in the Enacted Balloon-Car Curriculum

1. Messing About. Working in small groups of three or four, students constructed a basic balloon car according to directions and with supplied materials, then used the remaining time to "mess about" with the materials and different configurations of the construction. Students collaborated on one car per group.

2. Sharing Observations. The class came together to allow each group to share its observations from Messing About with the whole class; the teacher directed the session and took notes on an overhead projector.

3. Selecting Variables. A whole-class white-boarding exercise distilled from the observations a list of potential variables that were thought to affect performance of the balloon car. In a round of voting, the class selected which variables to test, reducing the list to the number of small groups. Each group received one variable to test in Experiment I.

4. Experiment I. Each small group developed and ran an experiment to test the effects of its variable on the car's performance. Their experiments tested two or three different settings for a variable and ran three or more trials for each setting. The dependent variable was the distance the car traveled over a flat surface.

5. Poster Presentations I. Small groups prepared posters summarizing their experiments and results and presented them to the whole class, fielding questions from the teacher or their peers that were meant to be evaluative of their experiments.

6. Lecture Prelude. This was a short, approximately 7½ minute session that came after the first round of Poster Presentations and prior to a lecture on the physics concept of force (Force Lecture) during which the teacher asked the students to discuss in their small groups their ideas about how the balloon engine made the car go.

7. Force Lecture. The whole class received instruction in "forces in pairs" from the teacher, which included multiple demonstrations with student participation. The "forces in balloon" portion of the lecture situated the forces in pairs concept in the material circumstances of their balloon cars.

8. Experiment II. Small groups were charged with using results of their first round of experiments, feedback on their Poster Presentations, and the concept of forces in pairs from the lecture to redesign and re-run their experiments on either the same variable or one newly assigned from the class' earlier list. Students were given new dependent variables to test in addition to distance: velocity over the first one or two meters and force exerted by the balloon car measured with a spring scale.

9. Poster Presentations II. Small groups again prepared posters summarizing their experiments and results. In the second poster, students were instructed to present motion storyboards of forces acting on their balloon cars at different stages in its trajectory, explain their results in terms of forces in pairs, and provide a design rule of thumb. Again, small groups presented their posters to the whole class, fielded questions and received evaluative feedback from students and teacher.

Appendix B

Transcript Notation

Transcript notations are based on those developed by Gail Jefferson (Atkinson & Heritage, 1984).

1. Overlapping utterances

Overlapping utterances are indicated with square brackets around the words that overlap. When speakers are separated by columns in the table, a jointed line in tables links overlapping utterances.

Hannah	Will	Stephanie	Teacher
	What [the heck?]		
[We need another] balloon.			

2. Intervals between utterances

An interval of approximately 5 seconds is indicated by a back slash in the transcript.

Teacher: What makes your car go? / What does this tell you?

3. Transcriptionist doubt

Words of which the transcriptionist was in doubt are enclosed in single parentheses:

Hannah: You didn't make (them different)? Or we didn't make them different?

When the parentheses contain the words "inaudible" or "indistinguishable," or a question mark, it indicates no hearing could be achieved for the talk or string of words in question:

Hannah: We got to (inaudible) a new thing!

4. Actions other than speech

Double parentheses are used to describe actions other than speech:

Will: ((Blows some air into balloon.))

or transcriber comments:

((Scratchy audio.))

5. Characteristics of speech delivery

Punctuation attempts to capture characteristics of speech delivery. For example:

. A period indicates a stopping fall in tone, usually associated with completion of an idea being uttered.

, A comma indicates a continuing intonation, a pause, not necessarily between clauses of sentences.

? A question mark indicates a rising inflection, and is usually associated with a question.

! An exclamation point indicates an animated tone.

A single dash (–) indicates a halting, abrupt cut-off.

Ah Emphasis is indicated by italics.