# Design-based science learning: Important challenges and how technology can make a difference

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**Abstract:** The affordances of design activity for science learning are well-recognized. However, the implementation of design-based science learning in classrooms presents a number of significant challenges. We have been exploring some of these challenges in our design-based approach to science learning called Learning by Design (LBD). In this article, we describe two significant challenges we faced in implementing our LBD approach and present two strategies that we have implemented in our software, SIMCARS, to address them. We also present the results of a pilot study which suggest that when SIMCARS was integrated into one of LBD's science units, it helped the participants of our study to overcome the identified challenges of learning effectively from design activity.

Design-based science learning (DBSL) (Fortus et al., 2004; Kafai, 1996; Kolodner et al., 2003; Penner et al., 1998) continues to receive significant attention in educational circles because of the widely recognized affordances of design activity for learning. But there is also an ongoing discussion about the various challenges involved in implementing a DBSL approach in classrooms (Hmelo et al., 2000; Kafai, 1996; Kolodner et al., 2003; Penner et al., 1998; Schauble et al., 1995). We add to this ongoing discussion by focusing on two challenges that we have found in implementing our DBSL approach, Learning by Design (LBD) (Kolodner et al., 2003). First, we have to meet learners' need for explicit support for constructing scientific understanding from their design experiences. Second, we have to find ways to suitably complement the real world design environment, compensating for situations where the real world prevents learners from having the right kind of design experiences to be able to emphasize principled understanding due to time, material or environmental constraints. In this paper, we discuss these two educational challenges associated with DBSL and a technological solution involving our educational software package called SIMCARS. Addressing the first challenge, SIMCARS incorporates an explanation tool that scaffolds students to explain the design phenomena that they experience in "scientific" terms, enhancing their abilities of connecting observed physical phenomena to the underlying science content. In order to address the second challenge, we have included in SIMCARS a simulation-based design environment. SIMCARS' virtual design environment complements learners' real world design environment by including more possibilities for design than in the real world and by allowing investigation under conditions which cannot be easily made to exist in the real world. We will also discuss a study which shows that when we had learners use SIMCARS in the context of one of LBD's units, SIMCARS helped some students to connect their design experiences to the science content, enhancing their scientific understanding in the context of designing. It also showed potential to overcome many of the limitations of the real world design environment that were preventing the learners from learning effectively from a DBSL approach.

## Connecting design experiences to scientific understanding

One of the important challenges for DBSL is fostering scientific understanding in the context of design activity. Schauble et al. (1995) reported that the nature of design activity can often shift students' focus to creating outcomes rather than constructing understanding. We have grappled with this issue in our LBD approach. To address the challenge of helping learners construct scientific understanding from their design experiences, we previously introduced the *Rules of Thumb (RT)* activity into the LBD approach (Ryan & Kolodner, 2004). In this activity, a class converges upon a set of student-generated *rules of thumb* to guide their future designing based on an analysis of their past designs and design experiences. These rules are used by teachers to scaffold students as they connect their design decisions to the science governing the designed artifact. We have studied the implementation of the RT activity in one of our LBD units called *Vehicles in Motion (VIM)* - a physical science unit where students build, experiment with, and redesign model cars and their propulsion systems to learn about forces and motion. Our studies show that in cases where the RT practice was done well, students consistently use science to explain and justify design decisions and solutions, articulate science concepts and principles in a more "scientific" manner, and demonstrate better ability to use content knowledge in new situations.

But our studies also found that the success of the RT activity in bridging design and science depends on a number of factors that are beyond the curricular set up. Success depends on how well the teacher orchestrates the elements of the RT protocol and on the quality of rules that emerge, which in turn depends on the scaffolding that the teacher provides for students as they are generating these rules. Success also depends on how fluent teachers are with the science content. With fluency, they can better help students diagnose their "troubled" designs from a science perspective. With this in mind we began to ask the question "can we devise a technological innovation that shares some of the burden of bridging design and science?"

Our proposed solution to this educational challenge is an explanation construction tool. DBSL approach often requires students to iterate over their designs, making structural changes to their artifact each time, and seeing how close that takes them towards achieving the goals of the design challenge being addressed. The explanation tool will be used whenever learners are investigating the structural changes to their design. This tool will scaffold explanation of the accompanying behavioral changes in their designs using the science content they learn in the curriculum unit. This has two advantages. (1) It brings goal-orientedness to their use of science because scientific explanation is situated in the context of changes they are investigating; (2) by linking structural changes to behavioral changes, we provide specific scaffolding to bridging design and science. SBF theory (Goel & Chandrasekaran, 1989) says that modeling the behavior of a system requires one to consider the underlying causal mechanisms – if a system can be viewed as a *Function⇒Structure* mapping, then it is the *Behavior* that explains how a particular structure achieves a particular function via its internal causal mechanisms. Representing behavior requires one to take into account the organizing natural phenomena and the science that goes with it.

## Complementing real world design environment

The second challenge for DBSL deals with engaging learners in a wide enough variety of design experiences to be able to gain deeper understanding and with the issue of the extent to which students can realistically have all the experiences with concepts they need in the environment of the classroom. Each variation in a design only paints part of the science picture. To uncover the big picture of science concepts through design experiences, one has to explore many variations of the application of those concepts. In the real world, exploration of the design space is limited by time, material, and environmental constraints. Because there is only limited time and materials in classrooms to cover any specific topic, the speed with which learners construct their designs and the extent of variations that they can investigate effects the number of experiences they will have revisiting science and refining their understanding. For instance, in VIM learners may have to design and test many variations of model cars having different kinds of wheels with varying thickness and weight to understand that the net force involves a tradeoff between mass and surface area of the wheels. Although exploring a wide variety of designs and incrementally improving them are important from a learning perspective, the time and material constraints in the real world environment can sometimes prevent the students from carrying out such extensive explorations.

The real world is also confusingly complex. Sometimes it is difficult to highlight the important phenomena of a domain clearly and independently. Doing so may require downplaying complexities. For instance, studies show that students have difficulty with the concept of momentum even though it is a regular feature of the real world and they routinely take momentum into account in their everyday experiences (e.g., playing soccer, sailing) (White, 1984). This is because most real world situations do not satisfy Newton's second law in simple ways. The real world is complex with the constant presence of friction and gravity, which may even cause the real world to behave in ways counter to what the law says. The real world design environment can not only overconstrain but also overwhelm students with irrelevant complexities. It is difficult to have complete control over one's experiment in the real world in terms of repeatability and frequency of the occurrence of events. Unavoidable complexities, coupled with students' novice construction capabilities can lead to the inability of learners to collect fully consistent and precise data.

Our proposed solution to this challenge explores the use of a simulation-based virtual design environment to complement the real world design environment. Both design environments have unique affordances and limitations. Working within a combination of both real world and virtual design environments can maximize investigative potential. Our software, SIMCARS, was specifically designed for the VIM unit. Some of the features of its virtual design environment include allowing students to isolate and examine factors affecting their model car designs resistant to isolation in the real world, conduct tests in an idealized world that is less prone to complicating external factors, have more options to explore and experiment with (in terms of both the raw materials for design and the target environments for deploying the designed artifacts), and do so in a time-efficient way.

## SIMCARS: System description and design rationale

The two main components of SIMCARS are a simulation-based virtual design environment where the students can quickly design and test virtual models cars, and an explanation construction tool that scaffolds construction of scientific explanations in the context of designing.

### The virtual design environment

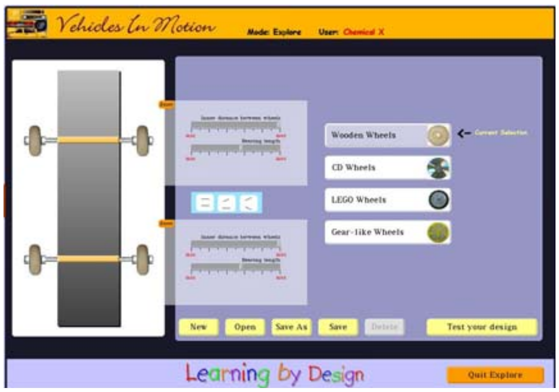


Figure 1. Virtual design environment

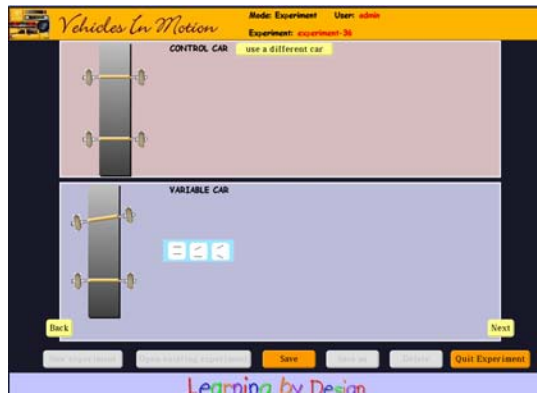


Figure 2. Experimental setup

A learner can interact with SIMCARS' design environment in two operational modes, the *Explore* mode and the *Experiment* mode. These two modes respectively support the two types of activities that occur in LBD classrooms, "messing about" and "experiment" activities (Kolodner et al., 2003). In order to understand SIMCARS' Explore mode, we have to understand the nature of *messing about* in classrooms – specifically, when and why it happens and what sort of support is needed there. "Messing about" is an exploration activity, geared towards helping learners become familiar with the design space. In this activity, learners come up with potential design possibilities by trial and error. Testing possible designs generate design-related issues and science-related questions that can then be investigated in greater detail. In a typical classroom session, students can explore at most three or four design variations. Designing in SIMCARS' environment affords quicker and more expansive messing about, leaving more time for detailed investigation. As shown in figure 1, learners can quickly configure a car by clicking on the various parts of the car and adjusting their parametric values. Learners can also compare two or more designs and make quick and informed decisions with the help of useful visualizations.

Compared to messing about, experimentation is more structured and hypothesis-driven. Here, once a question is identified to be investigated, being able to quickly experiment and get reliable answers is desirable. But neither is completely achieved in classrooms because construction takes time, and the world is complex and noisy. Interaction with SIMCARS in the Experiment mode takes the user sequentially through steps involved in designing and running an experiment: (1) capturing the question being investigated, (2) setting up an experiment by configuring a control design and a test design, and (3) running the experiment and getting feedback on the outcome of the experiment. Figure 2 shows a snapshot of Experiment mode. It depicts that particular step in the experiment where the students specify control and test designs.

### The explanation construction tool

We determined that experiments provide a good context for learners to engage in explanation activity because this is a key activity where they systematically investigate the effects of structural changes in their designs. We also decided that the explanation tool would be best launched in the Experiment mode between step 2 (after setting up the control and test designs) and step 3 (before seeing the outcome of the experiment). Upon launching, it prompts students as they make predictions about the outcome of their experiment. For instance, they would predict that "the control car will go farther than the test car." Then there would be an option for them to explain their prediction. If they choose to explain, the explanation tool scaffolds them in generating an explanation using the concepts and principles they learn in VIM. Once they are done with their prediction and explanation, they are ready to see the actual outcome of the experiment accompanied by a feedback on their explanation. They can run the explanation tool again here to explain unexpected results. Scaffolding for explanation takes the form of partially filled templates. Each template captures a portion of the causal model of phenomena underlying the outcome of the experiment. Providing the right explanation is reduced to completing the template, as shown in figure 3. Further scaffolding is provided by making the unfilled blanks in the template a multiple choice selection.

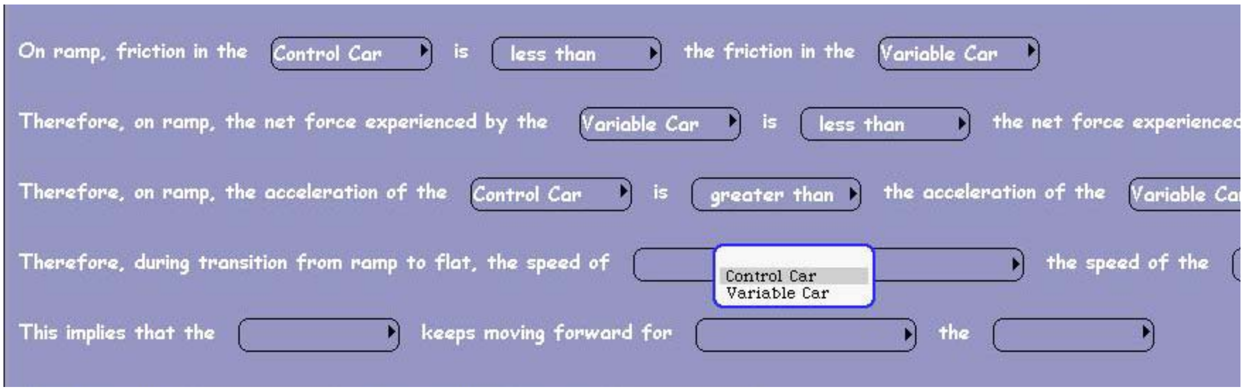


Figure 3. A sample template from the explanation tool

## Evaluation and findings

How well does SIMCARS help learners generate good explanations? If so, how does it contribute to the bridging of the design-science gulf among learners and contribute towards enhancing scientific understanding? How does working with the simulations contribute to the learning experiences of students? These are some of the questions we set out to answer in our pilot study.

Our pilot study was conducted in the context of an after-school program involving 16 students who were in 6th grade. We implemented a short version of the VIM curriculum, making sure the adapted version retained the "flavor" of the original unit. There were two learning segments in this unit. In the first segment, students focused on the Coaster car challenge to learn about forces, friction and gravity. A coaster car is a simple car pulled down a ramp and across the floor by gravitational forces. In the second segment, students focused on the Balloon car (coaster car plus a balloon propulsion system) challenge to learn about combination of forces. We made suitable modifications to the unit to integrate SIMCARS into the curriculum. Learners built a physical car as a first pass of the messing about activity. They then explored design variations in SIMCARS' design environment in Explore mode. Experiments were done entirely in SIMCARS. They ran experiments to gather evidence and create and justify design rules of thumb. Our study was qualitative in nature. Since the researchers were also the instructors for the unit, our data came in the form of video recordings of the sessions and field notes written "in retrospect" immediately after each session.

### Transformed science talk: effects of bridging

During initial stages of the unit, consistent with the first challenge mentioned above, we noted from classroom discussions that some students were indeed "lost" in the world of design and did not relate their design activities to the science concepts underlying their designs. Their designs were more informed by trial and error than by their conceptual understanding. We also noted that some students were equally "lost" in the world of abstract concepts and did not apply their conceptual understanding to their designing. Even though such students' "science talk" was above the ordinary, their designs suffered from the same problems that were seen in those of other students. But as the sessions progressed, discussions in the class became more sophisticated. In sessions following SIMCARS activity, we found that the discussion was not only maturing but also that students' science talk paralleled the explanations elicited from them using SIMCARS explanation tool. The following is an illustration of how a particular student's science talk changed over the course of the unit.

During the initial stages of the unit, in response to instructor's question about why one choice of axle-wheel arrangement (axle is fixed and the wheels spin around the axle) was better than the other (wheels and the axle spin as a single unit within a straw acting as a bearing), the student replied:

> ***Student:*** *… because with the wheels spinning instead of the axle [it] will create more friction, because spinning of the wheel will [create] friction with the axle. Then the car slows down.*

A little later in the unit after SIMCARS was deployed and used, in response to instructor's question regarding a particular design choice to keep the bearing's length shorter, the following conversation with the same student ensued:

> ***Student:*** *… they rub against the nut, against the wheel, which is bad, cause the rubbing causes the friction.*
> ***Instructor:*** *We'll know what happens then, right?*
> ***Student:*** *the car won't go very far*
> ***Instructor:*** *why?*
> ***Student:*** *well, if the friction is more, the car has less force pushing it on the ramp compared to a less friction car, causing less speed up. So, when the car comes off the ramp it carries less speed with it.*
> ***Instructor:*** *So less speed means*
> ***Student:*** *less speed means less travel, car doesn't go that far.*

Our analysis showed that the reasons and explanations offered by at least some students incorporated appropriate scientific vocabulary after they used the explanation tool. This was in accordance with our prediction about the effects that "bridging" design and science would bring about.

## More exploration, more gain

It is not possible for us to accurately estimate how many designs every group explored using SIMCARS. However, we closely followed one group's messing about activity. That group explored approximately twelve different variations of designs in less than one after-school session, compared to three or four when working with physical models. A more extensive exploration of the design space helped at least some students in their discovery of variables affecting the performance of their vehicles. For example, early in the Balloon car challenge, students constructed and tested their first physical versions of their cars. In the classroom discussion that followed, we asked them to identify the variables that affected their vehicle designs. They were able to identify only two variables - the number of balloons on the engine and the number of straws forming the nozzle of the balloon engine - both easily perceivable. The actual number was at least four. They had left out the length of the straws (nozzle) and the number of layers of balloons. The SIMCARS exploration activity followed. In the discussion that followed, students identified all the four variables.

While we expected more exploration in SIMCARS' design environment and better science learning from it, we discovered two more advantages of quick and easy exploration made possible by SIMCARS. The first advantage relates to motivation. Early in our study, we observed that some groups or individuals were not motivated enough to bring their (on paper) design ideas to fruition. The realization of conceptual design ideas in the real world involves the intermediate step of construction, which can take significant time. Some students were reluctant to invest their time in construction of variations of what they had already constructed before; instead, they wanted to "move on" to designing other types of vehicles. While their designs often looked good on paper, they were not well-realized through robust construction. As a result, the performance of their vehicles suffered – not due to bad conceptual design but due to bad construction, the chief reason being lack of students' motivation to pay sufficient time and attention to construction. These problems did not arise when designing in the SIMCARS environment. Learners could easily put together their designs by the click of a few buttons in the virtual world, test them immediately, and receive feedback. SIMCARS provided an alternate medium for some students to complement their real world design-based learning. The second advantage relates to confidence. We also observed that some students were "construction phobic." These students were inherently reluctant to build things with their own hands. While they chose not to participate in construction directly, their overall participation and contribution to the conceptual design was valuable to their groups. In SIMCARS, students did not have to worry about construction woes. Therefore it seemed to level the playing field for such "construction phobic" individuals or groups. In fact we noticed this in our data. We found that the designs of all the individuals, whether construction phobic or not, converged onto a best design in the SIMCARS environment. All the students figured out the right combination of parametric values for their virtual designs, and in the end, all of them were able to build the best car possible.

But not all of our results were as positive as we would have liked. Our analysis indicated that not all students derived full learning benefits from the explanation activity. Concepts related to nonobservable vector quantities like velocity and its relation to quantities like gravity and friction remained confusing for some students. More analysis is required to determine the reasons behind this observation and their implications for the explanation tool in particular, and LBD in general.

## Discussion

Our results suggest that integration of SIMCARS into a DBSL unit like VIM will have a positive impact. The benefits of using the virtual design environment - reducing the time and effort involved in realizing designs and testing them, expanding the possibilities for designing, removing some of the hard constraints present in the real world, reducing the irrelevant complexities and highlighting the phenomenon of interest – not only helped our participants meet some of the challenges of learning from design activity, but also allowed us to implement our DBSL unit in a meaningful way in the short amount of time that was available to us (The actual VIM unit runs for 30 days, and we had only 15 days). The advantages of SIMCARS' design environment could be misread as implying that designing real artifacts in the real world can be avoided. This is contrary to our opinion. Designing and conducting experiments on real artifacts have significant value for learning. (1) Producing tangible artifacts is sometimes more motivating and promotes a deeper sense of having actually "made" something; (2) interaction with tangible artifacts is more embodied and natural. They provide more manipulability, thus being more open to subtle and creative variations. We do not recommend a replacement of physical designs. We suggest, instead, that simulations offer important complementary benefits.

When one looks at the literature on the use of computer simulations for learning, the general conclusion is that there is no clear outcome favoring the use of simulations to promote learning without providing the appropriate scaffolding (De Jong, T., & Van Joolingen, W. R., 1998). Varying degrees of learning outcomes can be effected through the use of simulations by combining them with other forms of instructional support, ranging from simple support for planning and monitoring of exploration to more elaborate support for structuring discovery learning processes (De Jong, T., & Van Joolingen, W. R., 1998) and, in some cases, even providing support for learners to construct their own models that run the simulations (Jackson et al., 1996). Our research effort is related to these, but does not exactly fit into the same category. In the category of the cited cases, simulation and modeling are the primary conduits for change and central to the learning process. In our case, however, learning process is centered around designing artifacts, and the role of simulations is to expand the design environment to compensate for some of the limitations of the real world; take away the simulations and there is still our DBSL process. But we have tried to incorporate a number of useful principles suggested by research on educational simulations (e.g., ThinkerTools (White, 1984)) in designing our simulation environment (e.g., representing the phenomena of the domain clearly, eliminating the irrelevant complexities from the simulated world, encouraging better ways of representing and thinking about the domain).

SIMCARS' explanation tool is comparable to many research efforts that employ technology for enhancing learners' conceptual understanding by engaging them in model-building (e.g., Model-It (Jackson et al., 1996)). But there is a key difference. Instead of modeling the system in its entirety, the explanation tool allows learners to capture only the local changes they make to the system and their scientific understanding of the effects that follow. We claim that this form of local modeling is more appropriate for the DBSL approach because our context is such - learners are always making incremental changes to their artifacts in pursuit of their design goals. Local modeling is more connected to their ongoing activity. Therefore the explanation tool has more potential to be seamlessly integrated into DBSL approaches than more traditional model-building tools.

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