Design Rules of Thumb – Connecting Science and Design

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One approach to improving science literacy is to see that students make connections to real-life situations; to use science and science processes to "make decisions" and "understand the natural world" (NRC Standards). One goal in Learning by Design™ (LBD™) is to help students not only understand how science really works, but to offer them many opportunities to transfer what they have learned in class to real-world situations. We want students to be able to relate classroom experiences and knowledge learned in the classroom to situations outside of school and outside of the context in which the knowledge was learned. This is transfer. Bransford and Schwartz (1998) claim the belief in transfer lies at the heart of our educational system. Student ability to transfer is what LBD™ hopes to enhance greatly, and in turn, positively affect the science literacy of future generations. This paper presents a ritual, *Rules of Thumb*, developed and implemented in Learning by Design™ classrooms, to assist in promoting transfer and eliciting articulation of science principles in context. Previous research on transfer and learning supports the effort and methods employed. Furthermore, the origin of this practice and its initial results illuminate the potential of the approach as well as how to best put Rules of Thumb into practice for this purpose.

In order to facilitate deeper and longer lasting understanding of science, Learning by Design™ (LBD™) immerses students in design challenges that target science concepts utilizing inquiry strategies. One particular unit, *Vehicles in Motion*, challenges kids to design a car that is eventually self-propelled and will successfully negotiate a test track. Students iteratively redesign a vehicle and several propulsion systems and learn about forces and motion so as to meet the criteria of the design challenge.

Groups in a LBD™ classroom simultaneously work toward a solution, but that does not mean that all groups address the challenge in the same ways, investigate the same variables, or design the exact same product. For example, in building a simple coaster car, students have many choices to make: they have the freedom to use wheels that we provide or to substitute wheels of their choosing, they choose what type of bearing to employ, they can determine the length of the wheelbase, they choose where to place the axles on the chassis, they decide where the wheels will sit on the axle, etcetera. Through guidance from the teacher and their own knowledge of designing and running experiments (a skill focused on and built upon in the introductory *launcher unit*), students investigate the effects these differences in design (variables) have on the performance of the car.

After design teams complete experimentation, the class reconvenes to discuss their findings. Many times several groups will unknowingly investigate the same variable, and their results suggest the same effect is produced when altering that variable. Other teams may not have investigated the effect, yet it is a piece of information that is vital to their success also. As a result, the class begins to see that there are basic design features that all groups should notice and incorporate. These are possible candidates for Rules of Thumb. With the coaster car, the use of straws as bearings for the axles produces a significant increase in performance over other bearings (e.g., a styrofoam block or a folded piece of cardboard) because of its low friction surface and shape. The teams that recognize the significance of employing straw bearings have vital information to communicate to the rest of the class that may prove to be a mainstay in the final designs that all of the teams create.

Originally, when the LBD™ team saw this sort of convergence toward a single piece of useful information, they recognized the need for students to record the information. Many times, teams would not remember to incorporate some of these very important pieces of information, and it led to a lot of frustrated and lost students muddling through the design and inquiry experience. Also, groups would omit a key design technique, previously discovered and shared, that would jeopardize their chances in future activities. Important concepts were being obscured and lost in the flood of data being collected.

Thus, the creation of Rules of Thumb charts as a key LBD™ component. We discussed the idea of Rules of Thumb with teachers. We asked teachers to write down and post Rules of Thumb in class as they were generated. As the idea was piloted, several variations arose:

- Rules of Thumb would be a list of fabrication techniques that related to the use of materials. *Example-Use tape to secure bearings to the car because it can be removed and reapplied the easiest (compared to glue).*
- Rules of Thumb would be a list of design choices that seemed to be applicable across various car designs. *Example-Keep the wheels positioned far away from the chassis so that they do not rub on the chassis.*
- Rules of Thumb would be statements born of the experiments groups ran in order to understand the effect of a design choice. *Example-Use straw bearings because they allow the car to travel farther than any of the other bearings.*

Teachers enjoyed helping students generate Rules of Thumb; students used them fruitfully in designing, and the ability to extract out a Rule of Thumb from an experiment became an evaluation method that students used to judge the believability of their own experimental results and those of others. But when we observed to find the ways that Rules of Thumb were affecting students' ability to "talk science," we found that they were not playing a powerful role we thought they would play –

helping students connect their designing to the science they were learning. Seemingly, to the students, the design of their car and the science principles governing the behavior of their vehicle were related, but they were distant relatives. Laws of physics were *illustrated* by their car's behavior but had little influence on *design*. This belief is obviously antithetical to the aim of LBD™. Our intention in creating LBD units was that students would apply the science they were learning to their designing, and in the process of reasoning about how to do that application and explaining results, their understanding of science concepts would be enhanced. One of our teachers (the first author) suggested that if we made definition and use of Rules of Thumb more systematic so that they specifically connected science to designing, then we'd get the power they needed to be providing.

A New Ritual

To see how that might happen, consider the Rule of Thumb stated earlier about use of straw bearings:

> *Use straw bearings because they allow the car to travel farther than any of the other bearings.*

Straw bearings work better than the other available kinds because there is very little friction between them and the axles. This Rule of Thumb provides an example of how a low-friction surface produces less negative acceleration in a moving body – exactly what Newton's First and Second Laws tell us. If we could help students connect their Rules of Thumb to the reasons why they are working, then we'd be providing them with a way of internalizing the logic of Newton's Laws – learning the laws and experiencing the ways they apply at once. The teacher began asking students to write Rules of Thumb using this format:

> **When** <u>(describe the action, design, or choice you are working within)</u>,
> **use/connect/build/employ/measure** <u>(list your suggestion or method)</u>
> **because** <u>(list or supply the science principle or concept here that backs up your suggestion)</u>.

Student responses came to include more scientific terminology and to illustrate understanding of scientific principles, as in the following example:

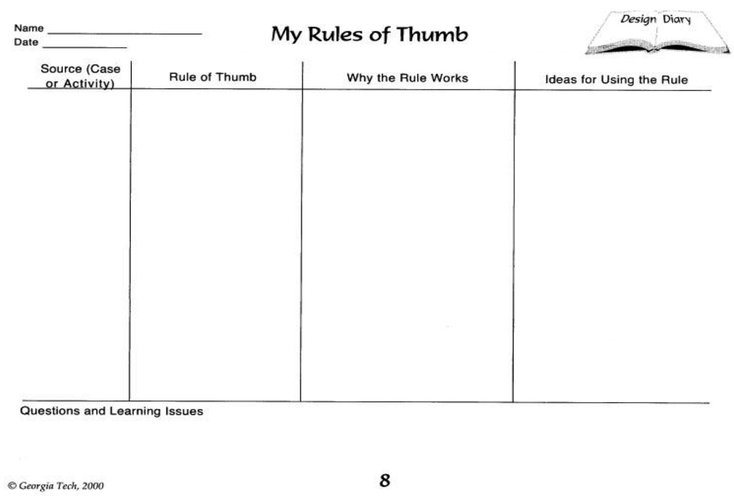
When choosing a bearing for the coaster car, use the straw bearings because the straw has very low friction and will not cause the car to slow down as much as the other bearing options because of changes in the net force.

When used in this manner, Rules of Thumb indeed began to function as a bridge between the concrete world of direct experience and the abstract world of physical law. They simultaneously serve the cognitive purpose of generalizing a theory from data, broadening its context, and the design purpose of making abstract laws of physics usable.

During the 2000-01 implementation of LBD™, we've designed and run an investigation to systematically compare the two uses of Rules of Thumb. Two teachers attempted a version of the use of Rules of Thumb that connects science to design (experimental condition). Two other teachers who are quite adept at using Rules of Thumb in their original form formed the comparison condition. We chose the two teachers for the experimental condition based on a perceived match between their teaching styles and the ways we wanted these new Rules of Thumb to be used. We helped these two teachers learn how to help their students create Rules of Thumb that focused not only on the design technique itself, but also on the science governing the success of the technique. An emphasis was placed on students formulating and expressing Rules of Thumb iteratively, making their applicability conditions (the 'when' part) and their scientific explanations (the because part) more complete and correct as their knowledge and experiences grew.

Reliance on context in memory and recall is fundamental to case-based reasoning, which lies at the root of LBD™. However, scientific laws have a very abstract context, not directly tied to specific experimental situations but rather to general classes of situations (this gulf is what made it difficult for students to apply them previously). Research has demonstrated that the similarity between multiple situations (or problems) is the single greatest factor influencing that student's success in transferring knowledge or principles learned from a previous, familiar situation to a new, unfamiliar situation (CTGV, 1997; Eich, 1985; Lave, 1988; Glaser, 1984). However, some *roots* of the context obstacle have been uncovered, and practical strategies for dealing with the problem of context have been devised. Our new approach incorporated several strategies to combat the influence of specific context on transfer. The students in these classes used a new Design Diary Page, the *My Rules of Thumb* sheet. This tool combined with modeling, bridging, and hugging techniques (Fogarty, 1992) served to establish a ritualized process of developing Rules of Thumb , and the use of "what if" questioning (CVTG, 1997) and principle isolation (Gick and Holyoak, 1983) looked to increase transfer and articulation. All teachers have this tool available to them as a part of the Design Diary, but only our experimental teachers were asked and trained to use the sheets in the new way.

Students were supplied with as many of these pages as they needed, and the teacher modeled their use. Students recorded the Rules of Thumb they had discovered as well as the ones suggested by their peers. The teacher, in the beginning, modeled justifying Rules of Thumb using science. Eventually, the classes began to realize that they lacked the underlying science and that they needed time to research a principle. At those times, the teacher would show a series of demonstrations, assign readings or investigative homework, use guided questioning to help the students realize that indeed they knew the principle, or offered transfer activities and mini-lectures to expose the science.


Name ____________
Date ________

My Rules of Thumb

Design Diary

Source (Case or Activity)	Rule of Thumb	Why the Rule Works	Ideas for Using the Rule

Questions and Learning Issues

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Students then return to the *My Rules of Thumb* page to fill in the "Why the Rule Works" column. Over the course of the unit, this process was repeated, with the teacher attempting to take a smaller role and encouraging the students to write justifications on their own.

Impressions

We have not evaluated the full set of data we've collected from these teachers' classes, but looking at the Rules of Thumb that were produced in experimental and comparison classes towards the middle and end of the ***Vehicles*** unit provides some striking impressions. Below are examples of Rules of Thumb focusing on construction, design, and experimentation with rubber-band and balloon-powered vehicles.

Rules of Thumb from Experimental Classes	Rules of Thumb from Other Classes
•Make sure the rubber band is (wound) tight when you put it on your car because the tighter the rubber band the more force and potential energy it has.	•Wind up the rubber band tight to the knot and so that it won't break.
•Use more balloon engines per car because then there is a greater amount of air (force) acting to propel the car without adding a lot of mass.	• Use 3 balloon engines because it gives it more force.
•Keep the exhaust of the balloon engine parallel to the ground because the direction of its (air's) force should be in the direction you want to go because when the air and the balloon interact, they each experience equal and opposite forces.	•Point the straws straight because it made the car go farther.
•Using more rubber bands in layers increases the distance the car travels because the more layers the (greater) the force, when force is increased, acceleration is increased.	• The number of rubber bands to use in an engine is 4 rubber bands doubled up because it goes faster and longer.

The chart shows that students were indeed recording more science when they were creating Rules of Thumb, but what effect did that have on their understanding of the science at the end of the unit and their ability to apply it? We look at the products students create at the end of the unit to find that out. At the end of the *Vehicles in Motion* unit, students are asked to write a 'Product History' of their vehicles. Students explain the evolution of their design, but more importantly they are asked to explain how science principles played a role in their design decisions. This data, and other assessments, are still being reviewed; however, preliminary results are showing some noteworthy trends. In the Product Histories (small sample reviewed), students in the experimental classes tend to reference science principles more often than the students in other classes when explaining their design decisions. Furthermore, there is evidence that the experimental students used the terminology at a deeper level and more appropriately. We are anxious to see if their responses in structured interviews and on unit-end performance assessments (transfer tasks) elicit similar referencing of science principles. It is interesting to note that one of the comparison teachers utilized the *My Rules of Thumb* sheet to scaffold their approach to creating and recording Rules of Thumb. Despite its use (a method dissimilar to our experimental approach), we did not see many differences in the Rules of Thumb developed in this class compared to the other comparison class.

During the implementation, some key events stood out that in our minds seem to play a role in incubating powerful Rules of Thumb. As we reviewed the students' records of their Rules of Thumb, we could see the iterative process at work in the creation of their Rules of Thumb. We had asked teachers to push students toward iterative refinement of their Rules of Thumb, as they often wouldn't know the science at the time they discovered a Rule of Thumb, or when they applied a Rule of Thumb, it wouldn't necessarily work the way they had expected, showing them that their rules weren't completely specified or the science behind them wasn't completely understood. When we look at students' design diary pages, we indeed see that students frequently amended their Rules (evidenced by crossed out words/clauses **or** added words/clauses). Below is a re-creation of a *My Rules of Thumb* sheet from a student in an experimental class. The italicized portions indicate amended statements.

Source	Rule of Thumb	Why the Rule Works	Ideas for Using the Rule
Balloon, 12/7	~~•When building a balloon car~~ the engine should not touch the wheels.	•When the balloons touch the wheels it generates friction which changes the motion of the car.	•Design the engine so that it does not interfere with the wheels moving.
Balloon, 12/11	•Engine should not be too high above the chassis. •Use wider straws to let the air out of balloon faster. •By using more than one engine the car will go further and faster. •Double-ballooning, or more, makes the car go further.	•(Changing) the height of the engine changes the center of mass. •When the air escapes faster the car is propelled faster (*because of an increase in force on the air by the balloon, 12/18)*. •When there is more than one engine there is a greater release of air propelling the car faster (*because there's more total force, 12/18)*. •*Double ballooning increases the force pushing the air out of the balloon, 12/18*.	•Use only 2 cups to support the engine. •*Use wider straws, 12/18* (*or use more straws in one exhaust, 1/9*). •Use more than one engine. •Try to use as many balloons together as possible.
Balloon, 12/18	•Keep the straw straight and parallel to the ground to make the car go farther.	•The direction of it's the force should be in the direction you want the car to go. When the air pushes on the balloon, it should be pushing in the direction you want the car to go (*because when 2 objects interact, each experiences a force that is equal and opposite, 1/9)*	•Put the straw straight and parallel to the ground

An important set of lessons we wanted to learn from this investigation was "best practices" in helping students form cogent and well-justified Rules of Thumb. The experimental teachers took on several roles in this process that we are guessing were quite significant. Particularly important, we think, was their emphasis on Rule of Thumb generation as an iterative activity and the particular things they did to scaffold such iteration. As well, both experimental teachers helped students generate large numbers of examples of each targeted science principle at work. Demonstrations, references to common everyday experiences, and incorporating students' derived examples of forces and motion gave students a good variety of experiences applying each concept outside of the context of the *Vehicles in Motion* unit. Our teachers were able to provide this kind of help because of their firm knowledge of and fluency with the science being taught. This knowledge also allowed experimental teachers to help students interpret their examples or help them diagnose a troubled vehicle from a science perspective. Finally, these teachers were well versed in sound inquiry methodology and created an environment (through the LBD™ approach) where students found it meaningful to generate Rules of Thumb and understand their foundations.

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