Designing

Criteria & Constraints

When a designer is trying to design the best product she can, she needs some way to judge how good her design is. What does it mean for it to be best? Designers define "best" in terms of **constraints** and **criteria**.

Constraints describe the limitations designers are working under. There may be only a certain amount of time available. This would be a **time constraint.** The engineers at NASA trying to save the Apollo 13 spacecraft had only a certain amount of time available before the air filter was used up. A designer may have only a certain amount of money she can spend. This is called a **cost constraint.** There may be only certain kinds or amounts of resources available. These define **resource constraints**. Sometimes, too, designers are limited by **communications constraints.** They might have to communicate only by telephone, making it impossible to communicate using pictures. Or, they may have only a slow modem available, meaning that only simple graphics can be sent to someone else. Another kind of constraint is a **size or space constraint**, where a product being designed cannot be bigger or smaller than a specified size or needs to fit in a specified space.

Constraints are absolute limitations. They cannot be violated in a solution. Criteria are preferences that might or might not all be achievable. Designers work towards achieving the most important criteria as well as they can, keeping in mind constraints as they consider several alternative solutions.

Consider, for example, an architect designing an addition on a house. The owners of the house want to spend no more than $20,000, and they want to get a bedroom and bathroom out of it, with a walk-in closet and a separate bathtub and shower. They want it added on upstairs in their attic space. The architect is working with cost and space constraints – the addition can cost no more than $20,000, and it has to fit into the current attic. She can't change either of those specifications. She is working with a large set of criteria – the clients want the bathroom to be large enough for a bathtub and a shower;and the closet to be large enough for walking into. And although the clients don't tell her, she knows that they want the bedroom to be big enough to fit the furniture they already own, and they probably want it roomier than their current bedroom.

Specifications

In order to know whether they are fulfilling criteria well enough, designers usually try to frame criteria quantitatively (using numbers) so that they will be able to measure how well they are achieving each of the criteria. For example, how big, exactly, should a walk-in closet be? How big, exactly, does a bedroom that can hold a client's current furniture have to be?

When criteria and constraints are specified quantitatively, they are called **specifications**. The architect may turn the criterion of having a large walk-in closet into a specification stating that the closet should be 80 square feet. She may measure the current bedroom her clients are living in, find that it is 130 square feet, and decide that the new bedroom should be at least 150 square feet. She may look at other bathrooms that she knows about that have both a shower and a bathtub and figure out that the bathroom her clients want will need to be at least 100 square feet. She will then look at the space constraints and turn them into specifications as well. When she measures the attic, she finds that it is 15 feet wide and 20 feet long, or 300 square feet. She'll put all of these specifications into a chart.

Tradeoffs

Often (usually), designers find that they cannot satisfy all criteria given the constraints they are working under. When criteria cannot all be achieved given the constraints, a designer must decide which are the most important criteria and aim toward achieving those, while still doing the best she can with the other criteria. This is called **making tradeoffs**. For example, when the architect above finds that what her clients want takes more space than what is available in the attic, she must go to her clients and ask which of the criteria are most important and how small she can make each room in the bedroom suite and still fulfill the criteria. They might say that they must have a separate shower and bathtub but that the bedroom itself can be made smaller. Or they might say that the closet is more important, and a shower over the bathtub would be fine.

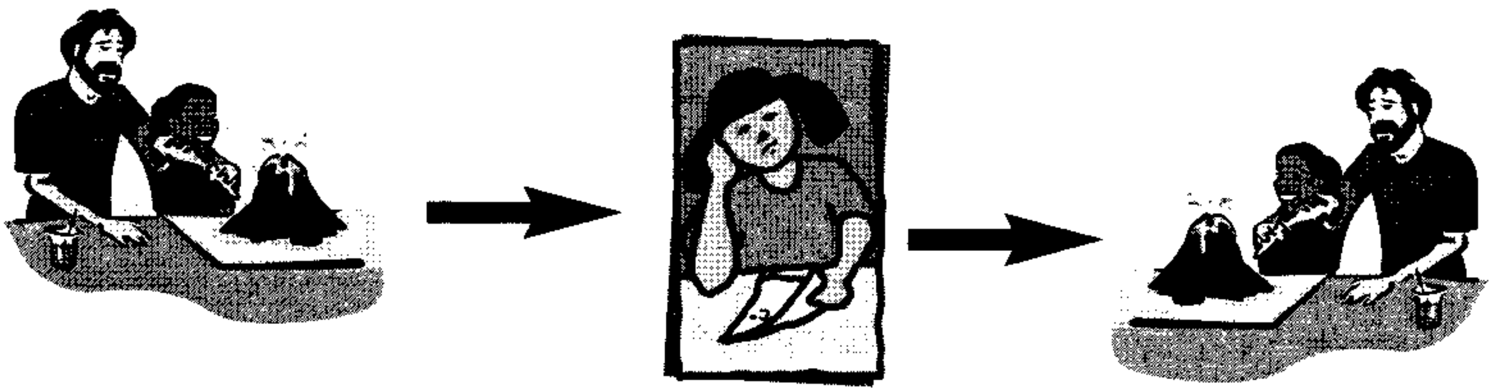
As they are deciding what they can do without, they might also add new criteria to make up for what they are losing. For example, these clients might decide that if the bathroom is going to be smaller, then they will need it to be lighter. Or they might decide that if the bedroom is going to be smaller, they will need to decorate it in a way that will make it seem larger.

Iteration

In design, refinement is an important part of the process. The best products are never from the first draft of the design; they are usually the result of many, many drafts. Early designs play an important role in the final product: they help us to identify weaknesses in the product, to refine criteria, to specify constraints more carefully, and to recognize special fabrication skills and materials needs. They help us find ways to streamline production, and to make a product that is cheaper to produce yet still meets the user's needs and preferences.

In a good design process, from first draft to last, there will be many steps. We call each stage of revising the design a new iteration of the design process. Typically, the best products have a history of many iterations.

One of the ways to get the most from a set of revisions is to get the opinions of other people who have worked on similar design problems. Others' suggestions and comments can help us to resolve problems and to notice aspects of the design that we hadn't attended to. Another way to get the most from iteration is to use case studies, comparing the current design to designs of products that have something in common with the current product. We can also look back at the history of a product's design -- to understand some of the ideas that worked well in the past, as well as those that didn't work out.



Keeping Track of Iterations

When something in our design doesn't work, our first feeling may be to throw away those failed plans. Don't! It's important to keep track of the history of a design. Why?

1. Sometimes, what seems like a mistaken approach turns out to work better when some other part of the design is changed.

2. We may need to remember what we did and didn't test.

3. We can save time by copying the working parts of a design directly, rather than rewriting them each time.

4. We can use our earlier designs to help teach others.

5. We can study our earlier designs, and learn how our mistakes and successes contributed to our current knowledge.

Keeping Good Records

There are several ways to keep track of design iterations. First, it's important to write down and illustrate design ideas as they develop. When you've tested out a design, you can write down what worked and what didn't, directly on the written plan or on a sheet that you keep with that plan. You should also write down all the new ideas that come up after such a test, so that if you don't test everything right away, you can remember your ideas for later iterations. We provide **Testing My Design** pages to help you.

Using Testing My Design Pages

It's important to keep a record of the performance of each of your designs. Use one "Testing My Design" sheet for each of your iterations. Then you'll have a record of what changes you made, how you tested, the data for that test, and what you learned from the test. This information helps your group decide what the next step should be:

- ★ Testing might reveal that you need to refine your design.
- ★ Your group might realize that you need to control your testing procedure more carefully.
- ★ As your group tests, you might find some additional criteria that you didn't consider, or that aren't part of the class's criteria list, but that are still worth sharing with the class. You might want to study such features more carefully.

Use as many of these sheets as needed for each separate design change. Group members' names should be on each sheet. It's also a good idea to keep track of design history by numbering and putting the date on each one.

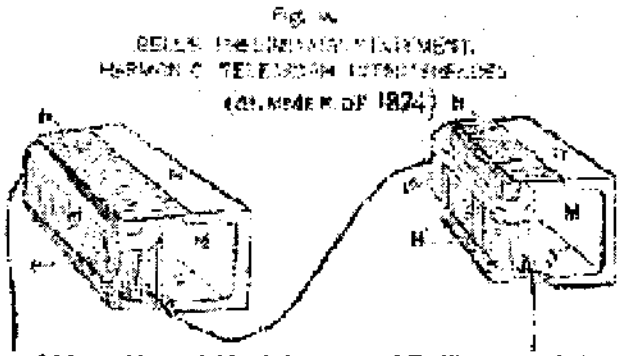
Communicating With Others – Keeping Good Records

Artists in the 15th century helped make scientific ideas advance. Artists like Leonardo da Vinci were able to depict objects in three dimensions instead of the two dimensions that earlier (Middle Ages) artists had been limited to. The depiction of objects in 3-D allowed scientists to graphically represent ideas they had about science and designs for scientific equipment (see picture of Harp model below). Before this breakthrough, only scientists who had exceptional spatial ability to visualize could 'see' mechanisms in their heads. Now, detailed drawings can represent the important features of an object or mechanism.

These drawings, along with the written word, became more and more available to people after the printing press was developed (designed!) in 1456. For example, in the 1450's there may have been about 60 Guttenberg Bibles available but by the year 1500 there were 15 million such books in print.

As ideas were being shared in writing and in drawings, artists and scientists together could do more.

Alexander Graham Bell, the inventor of the telephone, used drawings to work on his ideas and present his ideas to the patent office. His father-in-law encouraged him to keep careful records of his ideas so he could prove that his designs were the first and he could get credit for them. These patent drawings and the registration of his ideas also assured that he could sell his ideas and that he had the right to the money from the sales.



Picture of Harp Mental Model - one of Bell's records/ sketches with notes

Recording your test results

Lab notebooks have been used by many famous scientists and they are very useful to all of us. Any new idea that you might have after looking at your data could be recorded along side your data. You might begin to notice patterns in your data and in your ideas. Creative people often have several ideas (or insights) along the way to creating their designs. Keeping a record of those insights helps you to understand the importance of the process you've been through in your testing and thinking. It often keeps you curious about your work and pushes you along to do redesign and retesting!

Presenting to Others

Scientists, engineers, and designers make it a habit to present their ideas and results to others on a regular basis. You've already seen how much you can learn from your peers when you present to them or hear their presentations, and it is the same for professionals.

Scientists' and engineers' results are not taken seriously by the community until they have been presented to other scientists or engineers for confirmation. Scientists and engineers present their results to their peers in papers that they send to scientific journals and in lectures and poster sessions at conferences where scientists come together to share their results. They present their experimental designs and ideas to each other in research proposals. Before a scientist's paper is published, before she is asked to present a lecture or poster at a conference, and before she is given funding to run her experiments, the scientist's presentation is examined by scientific peers. This is called "peer review." A scientist's peers examine the experimental procedure, the data, and the way the data were interpreted to make sure that the procedures were run well and that the data interpretations make sense. Often, they ask the scientist whose results they are examining to rerun an experiment or to analyze the data a different way before they recommend publication, presentation, or funding.

Designers, too, must present to others, in "design briefs" and meetings with clients. In a design brief, the designer presents his design ideas to his peers in the design firm, making sure to justify all of his ideas taking into account criteria, constraints, and specifications, as well as science. Other designers in the firm comment on the designer's ideas, ask questions to find out more about the designer's reasoning, make suggestions about doing things differently, and point out things the designer might not have taken into account. The designer may then go back and do more work on the design to make it better. Designers working on big projects always present their ideas to their peers before making a presentation to clients. When designers present to their clients, they make the same kinds of presentations, making sure that their clients know how they are addressing all of the criteria, how they are managing tradeoffs, and to what extent constraints are being taken into account.

Presenting to Others (cont.)

Architects who are learning how to design participate in special kinds of design briefs called "desk crits" and "pin-up sessions." In a "desk crit," their teacher or a small set of other students sit with them at their desk while they explain and justify their design ideas. They make suggestions, and the design student iterates toward a better design. Later, when they are finished, they present their design ideas and justify them before a set of experts in a "pin-up session." The experts critique their designs in front of the whole class, make suggestions, and help classmates to reflect on how they design in order to become better designers.

In Learning by Design™, we have you make three kinds of presentations. You present results of investigations in **poster sessions**. You present design ideas to the class and justify them in **pin-up sessions**. And you present design experiences several times as you are constructing things that work and try to explain why what you are building behaves the way it does.

As with the presentations scientists, engineers, and designers make, your presentations serve several goals:

1. You can get confirmation from your peers about your results and ideas.
2. Your peers can help you recognize that you are confused about something.
3. You can get help from your peers in running experiments, interpreting results, refining your ideas, and explaining your design's behavior.
4. You can get new ideas by seeing the ideas of your peers.
5. You can see how others are doing things and learn better how to participate in the kinds of things scientists, engineers, and designers do – designing and running experiments and fair tests, justifying ideas and making informed decisions, and explaining.

One thing scientists and engineers have learned about getting helpful comments from their peers is that they need to make organized and clear presentations that their peers can understand easily. This is something you will have to do also. It will take time, and you might be frustrated early on – both because you'll find that your peers can't understand your presentations and because you'll find you can't always understand theirs. To help you develop the skills involved in making good presentations, we'll provide you with several kinds of help:

1. Design diary pages where you will record your ideas, procedures, results, and interpretations. You'll use these records to help you decide what to tell your peers.
2. Suggestions about what to talk about in each type of presentation.
3. Suggestions about how to do a good job at each of the scientific skills we want you to learn (listed in 5 above).

Pointers to pages for each of these are in the text where you need them.

Presenting Your Experimental Results

Poster Sessions

Up to now, when you've done presentations, you've shown each other artifacts: things you've designed, created, and tested. All the groups have been running tests rather than designing things. In this presentation, you'll be presenting experimental results to your peers. They'll want to understand:

- ✯ what question you were trying to answer in your experiment
- ✯ the procedure you used and why you thought it would answer the question
- ✯ the materials you tested
- ✯ your results

Remember from the Oreo™ Cookie Challenge how important it is to report the procedure you're using when you run an experiment. Each group might run their experiments differently, and it will be interesting to compare results from these different tests.

Preparing for a Poster Session

Make a poster that you can hang on the wall for others to see. The poster should include five kinds of information:

1. Questions you were trying to answer in your investigation.
2. Your hypothesis.
3. The procedure.
4. Your results.
5. Your interpretation of the results, including any rules of thumb (see page 107-109).

Make sure you're clear about:

- ✯ whether this was a fair test and why (see page 124)
- ✯ how confident you are about your results and why
- ✯ a clear statement about your group's interpretation and how confident you are of it

If you think the test you ran wasn't as fair as you had planned, you might want to report on how you would change your procedure if you had a chance to run the investigation again.

Presenting Your Experimental Results

Poster Sessions

Learning from a Poster Session

Be prepared to discuss your findings during the poster session. When listening to the presentations, it will be important to ask the questions you need answered, to understand results, and to satisfy yourself that the results and conclusions others have drawn are valid. Sometimes the class will need to send some groups back to re-do their experiments. Be sure that you believe the results other groups report.

Make sure that you can answer this set of questions after each presentation:

1. What was the group trying to find out?
2. How did they do it?
3. What did they learn?
4. What rules of thumb do their results suggest?

Reflection Questions

Probably the different groups in the class came up with slightly different findings and recommendations.

- ★ What different findings and recommendations were made?
- ★ Why do you think the findings differed from each other? Be as specific as you can. If you can remember the procedures people used, that might help you in answering this question.
- ★ Which experiments do you think need to be re-run?
- ★ What does everyone need to be careful about in making their tests fair?

Be prepared to discuss your conclusions in class.

Pin-Ups

When we've completed the first draft of a design or of a product, the opinions of other people can be very helpful in evaluating how well the design meets the criteria of the challenge. Students of design, engineering, and architecture have developed a way to give each other feedback during the design process. Different teams will set up their drawings, and each team will take turns presenting their designs to the rest of the class. The whole group of designers moves from one presentation station to another; at each station, they learn about the product or design, ask questions, and offer suggestions to the team whose product or design is being studied. They call this a *pinup session*.

The most important benefit of a pinup session is that different teams can learn from each other. A team that struggled with one aspect of its design may now have good advice for those who haven't yet tackled that problem.

Your First Pin-up Session

Architecture students use pin-up sessions to get feedback from their teacher and other students about their designs in progress. A pin-up session is good for getting advice and getting ideas, but it happens early in the process, before you've built anything.

As a presenter, you'll get your best feedback from others if you can be very specific about your design plans and about why you made your design decisions. You'll probably want to draw pictures, maybe providing several views. You certainly want everyone to know you expect your design to achieve the challenge.

As a listener, you'll provide the best help if you ask probing questions about the things you don't understand and if you are polite when you point out errors and misconceptions in the reasoning of others. These kinds of conversations will allow listeners to learn as well.

Preparing for a Pin-Up Session

Write down the answers to the following questions. These answers can be used in your team's presentation during the pin-up session.

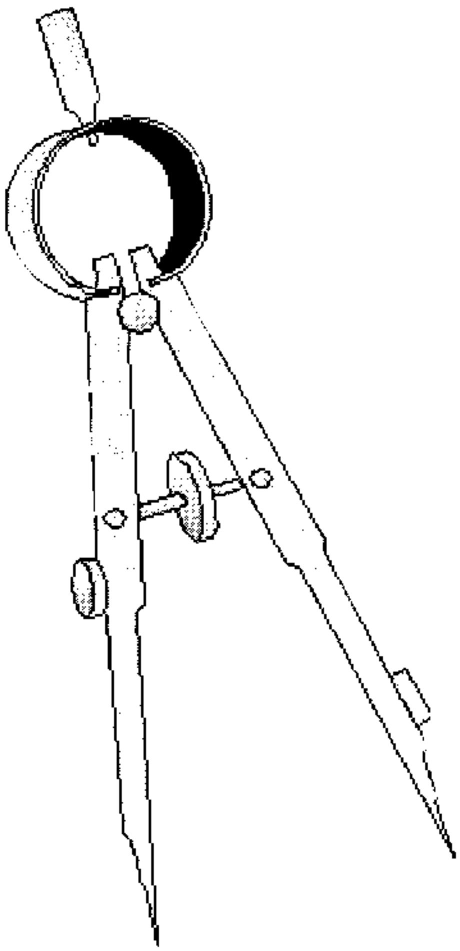
1. What features does our design have?

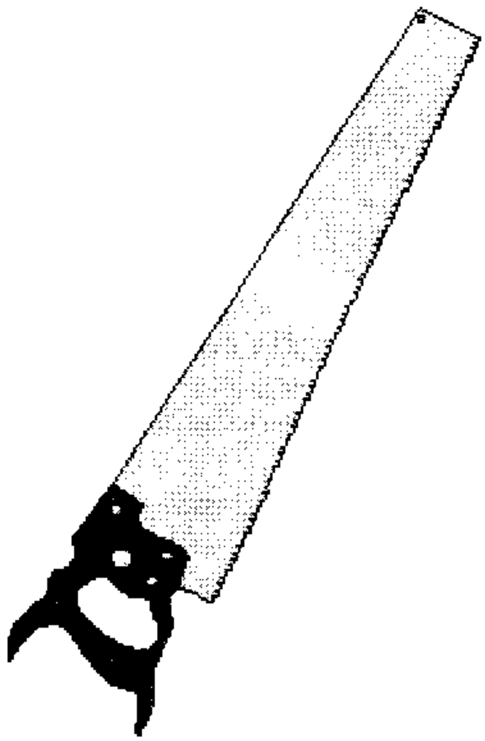
2. For each, what criterion will it achieve and why is this the right way to achieve that criterion?

3. Are there any problems we foresee with this design?

4. What do we predict will happen when we build it?

5. Is there anything we need help with?





Gallery Walks

When we've constructed the first iteration of a design or of a product, the opinions of other people can be very helpful in evaluating how well the design meets the criteria of the challenge. Students of design, engineering, and architecture have developed a way to give each other feedback during the design process. Different teams will set up their designs or the drawings for their designs, and each team will take turns presenting their designs to the rest of the class. The whole group of designers moves from one presentation station to another. At each station they learn about the product or design that is being studied. This session is like walking through an art gallery and observing each work of art, so we often call it a gallery walk. When only a set of plans is presented, we call it a pinup session.

A gallery walk is one step **in the middle** of a design sequence. Before this step, you will have worked in groups to design a solution to the current challenge, you will have built a prototype of this solution, tested it, and gathered and recorded data about how/whether your design worked. Students can also call a gallery walk when several groups seem unable to come up with ideas that move their designs forward.

The gallery walk provides an opportunity for groups to share what they have tried and what they have learned from their attempts. This is a great opportunity to learn from one another's comments and suggestions. Class members may provide a group with specific advice on design, fabrication, or testing. Remember, you can learn a lot from "failed" attempts, so be sure to study these as well.

The goal of a Gallery Walk is that all students should better understand the challenge, the variety of solutions that might work, which solutions are the most promising and why, and what both successful and unsuccessful designs reveal about the way the world works. Remember to use evidence to back up your comments.

Participating in a Gallery Walk

When you participate in a gallery walk, it's important to observe the design carefully, and to ask questions about how the design meets the criteria of the challenge. When your team is presenting, you need to explain your design and justify the decisions you made. You need to back up your design opinions with evidence (either from tests of the design or from similar cases that you know about).

Be prepared to ask (and answer) questions, such as:

Can you show us how this is constructed?
How well does it work?
How did the challenge constraints affect the design?
What cases or other knowledge contributed to the design?
What problems remain?
Did you try anything different?
What else do you want to test?

Design Rules of Thumb

Definition

In the past, you may have heard the expression, "as a rule of thumb..." as a way of measuring, estimating, or predicting. For example, "As a rule of thumb, a dollar bill's length is roughly 6 inches" or "The top part of the thumb is about an inch long." These statements are meant to help a person when they do not have the specific tool or a lot of time to measure something. A rule of thumb can also be an easy way to remember a standard for doing a task. For example, as a rule of thumb, you need at least five trials to know that your results are consistent.

In LBD™ classes, students spend a lot of time designing products and mechanisms. Many times, there are lessons about design that an individual, group or class can learn from their experiments. For example, in the Book Support Challenge, you learned that bundling cylinders together seems to hold the weight of the book better than only one or two cylinders. Each cylinder can withstand only a small amount of weight before it collapses. However, if we bundle the cylinders, each cylinder in the bundle only has to support a fraction of the book's total weight. Thus, the bundle outperforms a single cylinder. This is an example of a lesson learned through experimentation and iteration with different Book Support designs. It can be useful as you iteratively try to create a better book support or one that can hold up a heavier book or a support that can hold some other object, so it is a good candidate for a Design Rule of Thumb. A Design Rule of Thumb might look like this:

When building a support structure using a fragile material, bundle or attach cylinders of the material together for strong support. Bundling distributes the weight of the object across all of the cylinders, allowing the material to hold far more than it could if only a single piece of it was used.

Structure and Content

Notice that this Design Rule of Thumb gives the reader several key pieces of information.

1. It sets the situation, telling the reader "when" or "where" this Rule of Thumb might be appropriate.

"When building a support structure using a fragile material, ..."

2. Tells the reader "how" to accomplish the design feature.

"...bundle or attach cylinders of the material together ..."

3. Offers an explanation using science terms and reasoning as to "why" the action or design recommendation is a good one.

"...because the bundle distributes the weight of the object across all of the cylinders, allowing the material to hold far more than it could if only a single piece was used."

Rules of Thumb, (cont.)

As you move through LBD™ units, you will have many opportunities and needs for creating Rules of Thumb. You will be provided with a Design Diary page titled My Rules of Thumb. This sheet will allow you to record Rules of Thumb that you and your classmates create.

We have created a template, a sort of blank form, to help you start writing your own Design Rules of Thumb.

When (describe the action, design, or choice you are working within),
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).

Notice how the example above follows the template. Also notice that the columns from the My Rules of Thumb sheet provide the information you need to construct a good Design Rule of Thumb.

The Need to Revisit Rules of Thumb

You may not always be able to write a complete Rule of Thumb at a time when you notice a trend. Don't worry! Usually, this will be because you don't know enough science yet to know exactly when the rule applies. That's why the LBD™ cycle provides several opportunities for revisiting and revising rules of thumb.

Sometimes, when you apply a rule of thumb created in one situation to another situation, it won't work as expected, especially if you weren't real sure about the science that explains it. If you misunderstood the science, you might have created a rule whose conditions for application (the When part) were too general or too specific. For example, ... When you try to use a rule of thumb and you get poor results, what you might want to do is look at your understanding of the science behind it to see whether that can help you define it better. Or, if you don't know that science yet, you might seek to learn more so that you can make the rule of thumb more accurate.

It is useful to revisit Design Rules of Thumb to see if they are still correct after you learn the science that might apply to them. Many times, after you learn more science, you will find that your rules of thumb can be made more specific or general. Your teacher will help you learn how to do this.

Rules of Thumb, (cont.)

Creating and Using Rules of Thumb in Class

Because there is usually not enough time for every group in the class to do every investigation or experiment that is necessary to achieve a challenge, it will be important that you present good rules of thumb to your classmates based on your experimental results. When you collect data, if they are consistent across trials, you will find it easy to draw out very specific rules of thumb, for example a rule of thumb about how to design a book support or a parachute made of coffee filters. It is far harder, though, to design rules of thumb like the one shown in the previous pages. It applies to all kinds of structures in addition to book supports. It may also be hard to attach scientific explanations to rules of thumb.

For these reasons, your class will keep a public list of Design Rules of Thumb. You'll debate and discuss rules of thumb that are proposed by different groups, and when one is accepted, you'll add it to the list. As rules of thumb are used, someone in the class will notice times they don't apply, and the class will try to explain using science. After learning the science, you'll work as a class to fix the rule together and to attach science to the rule of thumb. This class list and discussion will allow you to not only give and receive help in creating good Rules of Thumb, but it will help you make better design decisions and help you identify the science that you need to know to do your best at designing.

Thinking Outside the Box: Reframing Your Problem

The Velcro™ Story

Throughout history, people have sought efficient ways to "fasten" objects together. Tape, shoelaces, buttons, and glue are all means of fastening, each with its own purposes, strengths, and limitations. Velcro is a fastener, a wonderfully multipurpose one, that was designed only recently.

In 1948, George DeMarshall and his dog came home from a walk covered in burrs. Mr. DeMarshall noticed how the burrs had "fastened" themselves to his clothes and to his dog's fur. He probably also noticed how strongly they stayed attached but also how easily they could be unattached. Mr. DeMarshall was curious about how this worked. Using a microscope to examine how the burrs fastened themselves to fur and clothing, he learned that the ends of burrs are shaped like little hooks that latch onto microscopic loops in clothing and fur.

Some people are always on the lookout for new ways to solve important problems. Mr. DeMarshall is one of those people. In his mind, he could envision a fastening material that would work like burrs do. Like burrs, it would be easy to fasten, hold tight, and be easy to unfasten. No fastening technique known up to that day had all of those properties.

Mr. DeMarshall envisioned Velcro™ as a two-sided substance where one side contained lots of little hooks like the burr and the other side contained places for the hooks to attach. Turning this insight into Velcro™ took some additional effort. He needed to develop a way to create the hooks, a way to manufacture such a device, and a way to market it.

Velcro™ is now its own company, and the Velcro™ products the company makes are used for a wide variety of products ranging from shoes to clothes to toys to construction to camping to army equipment. It all started when a curious designer noticed a mechanism in nature, made a connection between that mechanism and the age-old fastening problem, scientifically studied the natural phenomenon, and adapted that phenomenon for human use.

Curiosity and the desire to seek new ways to solve everyday problems allowed Mr. DeMarshall to envision a natural mechanism as a mechanical device.