APPENDIX A

Packaging Unraveled: The Inside Story

This section answers some of the questions raised in Chapters 1 and 2 and provides additional background material about packages and packaging materials.

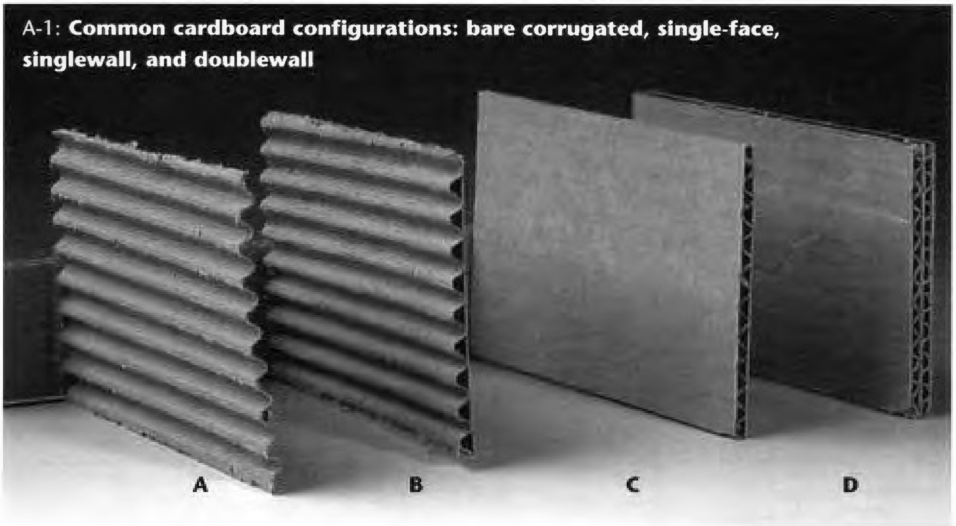
Cardboard Heroes

Cardboard is so widely used in packaging that the word *package* is often assumed to mean "cardboard package." It is estimated that about 90% of all manufactured goods in this country are at some point packaged in cardboard. Packaging includes more than the container that you see in the store, put in your shopping cart, and bring home.

Most prepackaged goods arrive at the supermarket on large wooden platforms called skids or pallets. On a skid, there are typically several dozen cardboard boxes held together with metal straps and/or shrink-wrap plastic. A typical carton may hold half a dozen to two dozen individual jars, bottles, or smaller cartons, which are the packages the consumer sees. On their journey from the manufacturer to the store, most consumer products travel in cardboard.

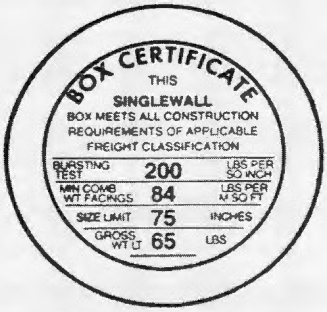
What, exactly, is cardboard? To a paper manufacturer, "paper board"—the industry term for cardboard—is nothing but a heavier, coarser grade of paper. Some cardboard comes in flat sheets, like the material of index cards, but most cardboard is sold in *corrugated* form. Corrugated cardboard is built around a fluted layer, also called the medium. It is the only part that is actually corrugated.

A corrugated layer or medium is shown in Figure A-1(A). The medium is then glued to a flat sheet, which the industry calls a facing, as shown in Figure A-1(B). This material, which is called single-face corrugated, is never used to make a carton, but is sometimes used as cushioning material—for example, to wrap glasses or mugs. Usually, another liner is added to the other side, as in Figure A-1(C), to make double-faced, or, as it is more



A-1: **Common cardboard configurations: bare corrugated, single-face, singlewall, and doublewall**

A-2: **Box certificate showing bursting test data**



BOX CERTIFICATE
THIS
SINGLEWALL
BOX MEETS ALL CONSTRUCTION
REQUIREMENTS OF APPLICABLE
FREIGHT CLASSIFICATION
BURSTING TEST 200 LBS PER SQ INCH
MIN COMB WT FACINGS 84 LBS PER M SQ FT
SIZE LIMIT 75 INCHES
GROSS WT LT 65 LBS

A-3: **Box certificate showing edge crush test data**

BOX CERTIFICATE
THIS
SINGLEWALL
BOX MEETS ALL CONSTRUCTION
REQUIREMENTS OF APPLICABLE
FREIGHT CLASSIFICATION
EDGE CRUSH TEST (ECT) 32 LBS/IN
75
WT LT 65

commonly known, singlewall corrugated. This is the material used to make about 90% of all cardboard cartons. For heavier cartons, another medium and facing are added to make "doublewall corrugated." Figure A-1(D) shows a piece of doublewall cardboard. As we have seen, the purpose of using corrugations is to make a structure that is strong as both a column and a beam (see Figure 2-20).

Most cartons have a box certificate printed on them, which provides information about the cardboard they are made of. Figures A-2 and A-3 show the certificates from two singlewall cartons. In both certificates, the last two lines give the "Size Limit" and "Gross Weight Limit," respectively. These limits are set for a particular grade of cardboard by truck and rail freight regulations. The size limit refers to the sum of all three dimensions of a rectangular box: the height + width + depth cannot exceed this limit. The weight limit includes the box itself, as well as the contents.

The top line of the box certificate comes in two varieties. Figure A-2 shows the most common type, whose first two lines indicate "Bursting Test" and "Min. Comb. Wt. Facings (Minimum Combined Weight Facings)," respectively. The Bursting Test gives a measure of how well the carton can stand up to pressure on its side. The pressure in a fluid is increased gradually until a rubber diaphragm bursts through the cardboard. The pressure needed to burst through, in pounds per square inch, is recorded as the "Bursting Test" data. It is a test of how strong the side, top or bottom of the box is when it is loaded.

The second line, "Minimum Combined Weight Facings," records the weight (in pounds per thousand square feet) of the two facings (flat sheets) of this singlewall cardboard. For this particular material, the sum is 84, or 42 lbs/1000 sq. ft. per facing (Figure A-2). By comparison, ordinary copy or printer paper weighs about 15 lbs./1000 sq. ft, or about one-third as heavy as the cardboard liner.

The box certificate in Figure A-3 is different. Instead of the Bursting Test and Minimum Combined Weight Facings, it has a single line called "Edge Crush Test (ECT)." This intriguing process consists of mounting a two-inch wide by inch-and-a-quarter high strip of the material so it is standing up, and pressing it with a machine until it buckles. The weight that it takes to crush the sample, divided by the width of its edge, is the ECT result in lbs./in. The ECT actually gives a better measure of the strength than the bursting test, because boxes most often fail by buckling at the bottom of a heavy stack. The ECT is a measure of how well the side of the box works as a column.

By far the most common type of cardboard container is the folding carton, which is delivered flat to the product manufacturer, to save shipping space. They are nearly always made of corrugated cardboard. Currently, the cardboard for these cartons is most likely cut and scored by automatic machinery, which helps to explain the relatively small number of standard shapes and sizes.

The form of most folding cartons is so common that the industry calls it the "Regular Slotted Container (RSC)." An example is shown in Figure A-4. The style of this box is sometimes called "the tube" because the sides are joined together, but the end flaps are initially open. The side joints may be made using glue, tape, metal staples, or metal stitches. In Chapter 2 we explored some of the pros and cons of these joining methods. To see why the RSC is so common, look at the folded out version in Figure A-5. It is almost perfectly rectangular. If any of the flaps were longer or shorter, more complicated dies would be required to make these cartons, and more cardboard would have to be thrown away to make the flaps.

A common alternative to the Regular Slotted Container is the same box with flaps on one side only. This type of box, which also uses tube construction, is called the "Half Slotted Container (HSC)." Because it is lacking one set of flaps, another piece is needed to form the lid, which has to be a little larger than the bottom. The lid could be another HSC, or another type of construction called the tray, which has a solid bottom or top and folding sides. Figure A-6 shows a Half-Slotted Container with a tray lid.

A-4: **Regular slotted container (RSC)**

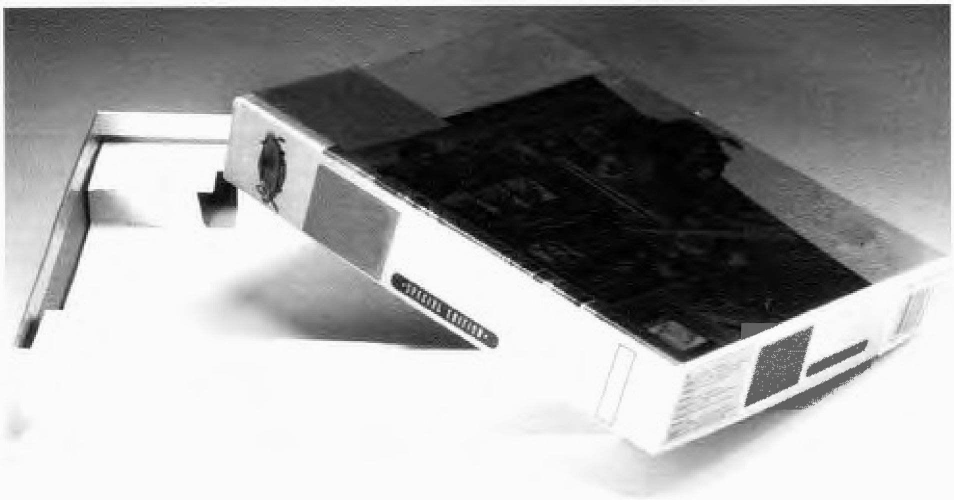
A-5: **The same carton, folded flat**

A-6: **Half slotted container (HSC) with tray-style lid**

The cardboard boxes described so far all require tape, glue, or metal fasteners to assemble them. There is a whole category of boxes that can be folded flat and assembled completely without using any of these joining methods. These boxes depend completely on clever design and friction to hold them together. Examples are shown in Chapter 1 and 2 in Figures 1-2, 1-18, 1-19, and 2-34. Note that both the bottom and the lid are of "tray" construction, and that they are hinged. There are all sorts of folding box designs, which fold and unfold without any joining, including tubes, trays, unusual shapes, cutouts. You can make your own collection of assorted folding boxes and examine how each one works.

In addition to the folding carton, there is a more expensive kind of box called the "rigid setup box." These are assembled by the box manufacturer and delivered to the product manufacturer ready to be filled (Figure A-7). They usually have a nice decorative finish to them. They are usually of the tray style of construction, with the sides attached by tape along their edges. Some setup boxes have hinged lids, while others have separate tops and bottoms. Cigar boxes are the most famous type of setup boxes with hinged lids.

A-7: **Rigid setup box with separate lid**



How Shopping Bags Fail

Shopping bags can and do fail unexpectedly, sometimes on the way home from the store. In Chapter 2, we outlined some suggestions for testing the strength of shopping bags. In this section, we will discuss three of the most common failure modes of shopping bags, and show how the concepts of tension, compression, and shear are useful in understanding them.

The most common type of plastic shopping bag has handles that are simply cut out of the body of the bag. The top may be cut square with notches for the handles below, or the handles may be raised above the top, as is the case with most supermarket bags. In either case, the most common type of failure, as every shopper knows, is for one of the handles to stretch and eventually tear apart when the bag is too heavily loaded (Figure A-8).

The tearing of the handles is an example of failure in tension. It occurs because of forces that are pulling away from one another in opposite directions, as shown in Figure A-11(A). The force pulling upward comes from the hand holding the bag. The force pulling downward results from the weight inside. The handles are stretched because they are the narrowest part of the bag, and all of the force from the weight is concentrated there. As they become longer, they also become thinner, just like a rubber band does when stretched. As the material becomes thinner, the force becomes even more concentrated, until the material simply isn't strong enough to manage so much force over such a small surface. At that point, the handles literally pull apart.

Nearly all paper shopping bags, and some plastic shopping bags, have handles that are made separately and then attached to the body of the bag. In plastic bags, these handles are usually "heat sealed" to the body—i.e., attached by briefly melting a small section of both body and handle together. With paper bags, the handles are nearly always glued. To make the glue joints stronger, paper patches are often glued to both the handle and the body of the bag.

A-8: **Shopping bag post-mortem: tension failure of handles**

Figure A-11(B) shows how the glued handles usually come off paper bags. This is a typical attachment, which has to support shear. When the shear load becomes too great, the glue joint between the patch and the handles fails, and the handle simply pulls out. An example is shown in Figure A-9.

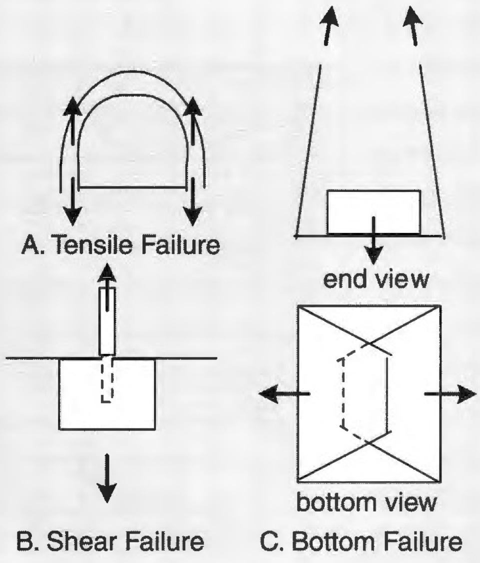
Nearly all paper bags have glued joints at the bottom, as well as at the handles. A common type of paper bag failure happens when the glue on the bottom stops working. The chain of events leading to bottom failure is more complex than the others, involving both tension and shear. An example is shown in Figure A-10.

As the end view in Figure A-11(C) shows, the upward force on the handles opposes the weight of the object in the bag. The bottom of the bag then acts like a beam. Its bottom surface tends to spread outwards, in tension, like the beam in Figure 2-18. The pulling outward is shown in the bottom view in Figure A-11(C). These opposing forces eventually make the bottom fail. One way for it to fail is for the glue joint to come apart—an example of shear failure. However, the glue may be stronger than the paper itself. Iin this case, the paper wil tear first, which is an example of tension failure. In Figure A-10, you can see places where the glue joint failed, as well as a few points where the paper tore.


A-9: **Shopping bag post-mortem: shear failure of handle attachments**


A-10: **Shopping bag post-mortem: complex failure of bottom**

A-11: **Three failure modes analyzed**



Anatomy of a Can

Until around 1970, nearly every metal can was made of steel. Although popularly known as "tin cans," there is only a very thin layer of tin plating, to protect the steel from rusting. They are also lacquered, for further protection. These cans are made in three pieces: the body, the top, and the bottom. The body is made by wrapping a rectangular piece of metal into a cylinder, and then joining the two ends. The top and the bottom are then attached separately. The side seam was sealed with a solder made mostly of lead. Recently, concern over lead poisoning has led to strict regulation of lead in food and beverage packaging, and the phasing out of solder-sealed cans. Nearly all three-piece cans now use welded side-seams.

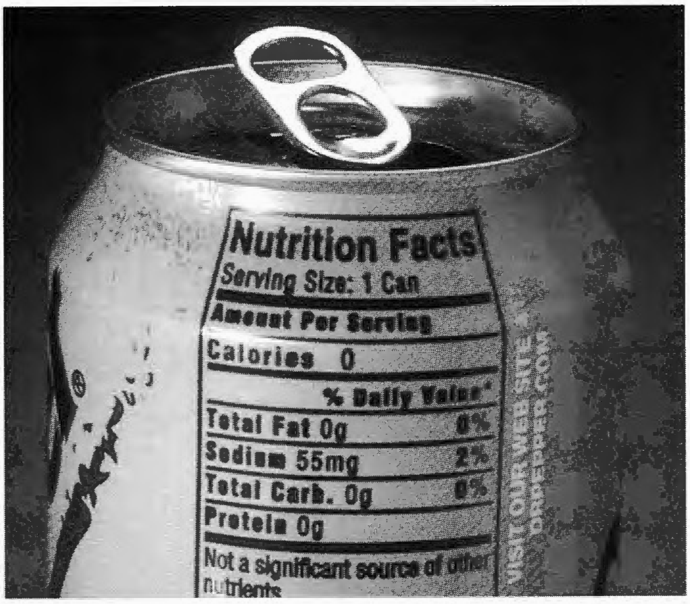
Aluminum is not nearly as strong as steel, but it does have some major advantages as a can material. Because it is softer, a disk of aluminum can be formed into a cup-shaped bottom by punching a deep depression in it. The only remaining piece is the top, so these are referred to as two-piece cans (Figure A-12). The top can be scored, allowing it to be opened with a pull-ring, which is not possible for steel tops. Finally, aluminum cans weigh about half as much as comparably sized steel cans, which lowers shipping costs.

A-12: **Stages in making a two-piece can**

A-13: **Aluminum can showing domed bottom**

The walls of an aluminum soft-drink can are extremely thin, as you can tell by seeing how easy it is to crush an empty can. (Crushing steel cans used to be a trick for weight lifters only!) The reason that the walls can be so thin is that the internal pressure of the soda helps to make the can much more rigid. However, this pressure could also make the bottom of the can bulge out. If this were to happen, the can would not have a flat bottom to stand on. (A similar problem exists for plastic soda bottles, as we shall see in the next section.) To counteract this tendency, the bottom of the can is domed, as shown in Figure A-13. As we saw in Chapter 2, the dome is a very strong structure, which resists the compressive forces coming down from cans stacked above.

Another interesting feature of the aluminum beverage can is the top. Why is it so much smaller in diameter than the body of the can (Figure A-14) ? The answer lies in the relative cost of the top, compared with the rest of the can. In order for the pull-tab to open the top, a small section of the top needs to be scored, so that it will break away easily. However, there has to be enough material under the score lines so that the can does not open prematurely. For the top to accommodate just the right thickness of scoring, it has to be considerably thicker, and therefore more expensive per square inch, than the rest of the can. Necking the top allows the can manufacturer to get by with less of this more expensive material. How much does this really save? For one can, not much, but what if you multiply by the 100 billion cans produced annually in the U.S.?



A-14: **Aluminum can showing necked top**

Decoding Plastic

Until the 1960s, very little packaging consisted of plastic. Since then, however, plastic has taken over an increasingly large share of the packaging market. More than a third of all plastic is used for packaging. It has some major advantages over cardboard, metal, and glass: it is cheap, easy to form into virtually any shape, and much less breakable than glass. Unlike cardboard, it is waterproof, and generally resistant to chemicals. Unlike metal, it does not corrode, and it is lighter than either metal or glass. Plastic can be colored or transparent, and most plastic used for packaging is also recyclable.

To aid in recycling, most plastic containers produced in the U.S. are stamped with recycling numbers. An example is shown in Figure A-15. What do these numbers mean? What information can be learned from looking at these numbers and the containers they appear on?

Recycling number 1 indicates Polyethylene Terephthalate, PET or PETE for short. PET is the only plastic material used to make carbonated beverage bottles. In 1977, Pepsi Cola invented a process for making PET bottles strong enough to hold soda. It involves blowing air into a heated slug of plastic, until it expands against a metal mold.


A-15: **Recycling number on the bottom of a plastic container**


A-16: **Bottom view of plastic soda bottle**

One problem with the method is that the walls become fairly thin. As a result, the bottom of the bottle has a tendency to bulge out, which can prevent it from standing up straight. The same problem was discussed above for aluminum soda cans. Until the early 1990s, a separate base of blue or green plastic was attached to the bottom of soda bottles to make them stand up reliably, but this required several extra steps in manufacturing. More recently, a process was developed that adds plastic to the base while the bottle is being blown. Additional plastic is injected at the very bottom of the base, which makes the base thicker, and forms the little feet which you can find on the bottom of any soda bottle (Figure A-16). The little button of plastic at the center (see arrow) is where the extra plastic was injected in.

One of the ironies of recycling numbers is that the "1" rarely appears any more on the bottom of soda bottles. The reason is that all soda bottles are made of this stuff, so recyclers already know what it is!

PET is also used to make audio and video tape, decorative balloons with metal coatings, and "fleece" vests and pullovers.

Recycling number 2 represents High-Density Polyethylene (HDPE). While PET is strong, the manufacturing process makes it impossible to add jug-style handles to the container. Containers with handles, such as one-gallon milk containers, are therefore made of HDPE. This material is also very resistant to strong chemicals, so it is also the material of choice for detergents and other cleaning fluids. However, HDPE is not transparent, so it cannot be used to hold any product that has to be visible through the container.

Recycling number 3 stands for Polyvinyl Chloride, or PVC, commonly known simply as "vinyl." At one time it was used for making liquor bottles, and was also a candidate for soda bottles. Currently, this material is not generally allowed for making food and beverage containers because it is suspected of causing cancer. However, some one-gallon water bottles are now made of PVC, which is the clearest of all common plastics. You can find PVC in many containers for hand soaps, shampoos, and other beauty care products.

Recycling number 4 symbolizes Low-Density Polyethylene or LDPE, which is chemically similar to HDPE (#2), but is much softer and more flexible. It frequently used for tops,

such as caps of plastic soda bottles. Because LDPE melts at a much lower temperature than PET, the top can be heated enough to be formed around the bottle, without softening the bottle. The pint- and quart-sized tubs for take-out food usually have tops of LDPE and bases of PP (#5 below). The bottoms can be microwaved, but the tops cannot! LDPE is also used to make garbage bags, most plastic shopping bags, and bubble wrap.

Number 5 indicates that the product is made of Polypropylene (PP), which is usually found in a semi-rigid, semi-transparent form. As mentioned above, PP is used to make take-out tubs, and also smaller tubs, such as those used for margarine and yogurt. Six-pack ring-holders are made of this stuff, as are cheese wrappers, inside liners for cereal and cracker boxes, medicine bottles, toys and a host of other products. PP can be microwaved.

Number 6 indicates Polystyrene (PS), which is the cheapest plastic. This is the material used to make those flimsy cookie trays, salad bar containers, thin transparent cups, and virtually anything else made of very thin plastic. Polystyrene also comes with the trade name Styrofoam, which is the same stuff with little gas bubbles trapped inside. Foams like Styrofoam are good for cushioning, because the little gas pockets allow the material to change shape and absorb impacts (see next section). The gas pockets also make Styrofoam an excellent thermal insulator. For this reason, Styrofoam is used to make insulated "hot" cups, insulated food containers, and coolers.

What Happens in a Crash

Why do some objects need to be cushioned, and others don't? What kind of material is good for cushioning and why? Fashion a ball of clay into a cup shape and drop it on the floor. It will change shape a little, but will probably stay intact. If the same piece of clay has been fired in a kiln, to make a pottery cup, it will probably break if you drop it on the floor. Silly Putty feels like clay, but if you drop it on the floor, it will probably bounce. Why do some materials change shape on impact, while others break and still others bounce back? Thrown hard, a rubber ball will bounce off the floor, get buried in the mud, or shatter a glass window. Why does the same rubber ball have such a different effect on these three materials?

The answers to these questions go straight to the heart of the atomic structure. Materials that bounce back, like rubber, are said to be *elastic.* These materials have long coiled chains of atoms. When compressed or stretched, these chains become more or less tightly coiled, but when released, the coils return to their original shapes. Materials that break easily like glass, chalk or baked cookies are known as *brittle* materials. In these materials, microscopic cracks create zones of weakness between layers of atoms, which relatively small loads can open up like a zipper, resulting in almost instant fracture. Soft, pliable materials such as clay, wax, or dough are considered *ductile.* When they are subjected to loads, layers of atoms shift and slip against one another, leading to a permanent change in shape rather than immediate fracture. Materials behave very differently because of differences in the ways their atoms and molecules are organized.

Suppose a box with an object in it is dropped. The object is likely to break if it is brittle, bounce back if it is elastic and change shape permanently if it is ductile. A common word for brittle is "fragile." When a fragile object is transported, there is always the possibility that someone might drop the package, or that there might be an impact from the side or top. Any of these impacts could break the object. The purpose of cushioning is to prevent it from breaking.

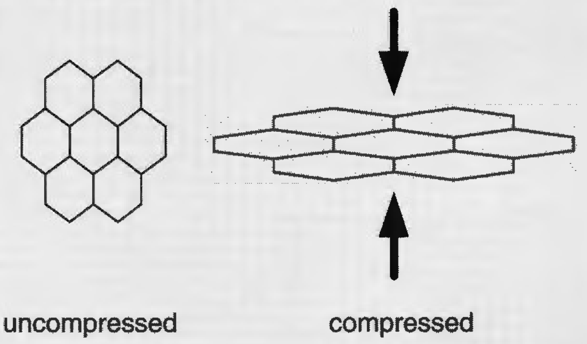
Cushioning materials work in a number of different ways to protect fragile objects from impacts. A coffee cup has a handle that is much weaker than the rest of the cup. Cushioning material helps to insure that the cup never rests on its handle, and that any impact absorbed by the handle is spread to the rest of the cup as well. By filling up all of the space inside a package, cushioning also prevents a fragile object from moving around and crashing into another object or the wall of the carton. Many cushioning materials have little air spaces inside them. These include corrugated cardboard, Styrofoam, foam rubber, and straw (Figure A-17). These materials not only fill up space but can also absorb some of the energy of an impact themselves by tightening up their own air pockets (Figure A-18).

For products that are not so fragile and that are fairly light, space filling may be the only requirement. Space fillers include particles such as sawdust or Vermiculite, shredded paper, crepe paper, and bubble wrap. These materials mostly deform permanently on impact. For example, in a serious impact, the bubbles in bubble wrap may pop. As a result, they cannot be relied upon to absorb much energy. Space-filling materials are used for small, relatively sturdy products. For example, the inside of a book-mailing envelope is filled with shredded paper or bubble wrap.

The most fragile objects require elastic cushioning that will absorb considerable amounts of energy, and do so repeatedly, in case the package is dropped more than once. The best materials for this purpose are foam rubbers, which are made of plastics such as polyurethane. When subjected to an impact, the cavities in the foam change shape, as shown in Figure A-18. Afterwards, they return gradually to their original shape. Because the original shape is restored, elastic materials are also ready for the future impacts. Light, very fragile objects, such as small electronic products, watches, and jewelry, are likely to be shipped in foam rubber.

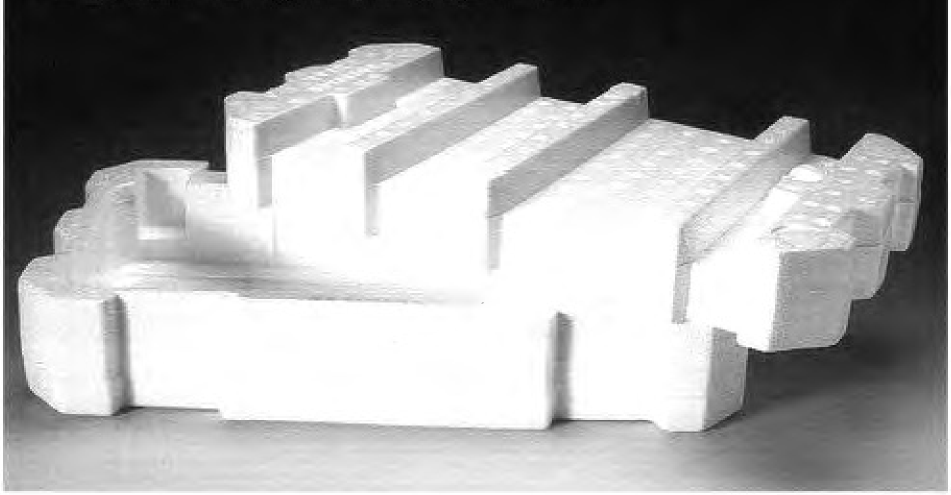

A-17: **Box with straw cushioning**

A-18: **How foams distort on impact**



Elastic materials are ineffective if the product is too heavy. A heavy product will pre-compress foam rubber just by resting on it, so that it can't compress any further on impact. For heavy objects, a semi-elastic cushioning material such as Styrofoam is needed (Figure A-19). Styrofoam is rigid enough to support a considerable amount of weight without compressing. It can then absorb moderate impacts and return part of the way to its original shape. Styrofoam can't absorb as much energy as foam rubber, but it doesn't need to, if it is being used to cushion something heavy. Because heavy objects can't easily be lifted very high, they aren't normally dropped as far. Styrofoam blocks, slabs, or molded caps are used to cushion large electronic products such as TV sets and computers.

A-19: **Styrofoam end caps for packaging a computer**



How Pump Dispensers Work


A-20A


A-20B

Pump dispensers are sold as part of the packaging of many thick liquids, ranging from hand lotion to mustard. Most people throw them out with the empty bottle, but these actually are fascinating devices that are worth exploring. A way to start is to keep careful track of what actually happens when you operate one of these pumps.

Figures A-20 A through F show the sequence of events in detail. In A, an empty pump dispenser is placed in the fluid for the first time. The plunger is pushed down in B, and then released in C. Notice that as the white plunger is released, the chamber just below it half fills with the fluid. Still, nothing comes out of the spout. Next, the plunger is depressed again, in panel D, and released in E. This time, the chamber becomes entirely filled with the fluid. Then the plunger is pushed down again in F, and fluid comes out of the spout!

There are really two separate operations going on here. First, the chamber has to be filled with fluid. This operation only happens on the upstroke. In this particular pump dispenser, it takes two upstrokes to fill the chamber completely. Other pump dispensers may require more or fewer strokes to accomplish the same thing. Once the chamber is full, the device is ready for the second operation: forcing the fluid out of the spout. When the plunger is pushed into a full chamber, there is no place for the fluid to go except out through the spout.


A-20C


A-20D


A-20E


A-20F

How does the pump dispenser do all of this? To answer this question, we'll need to look at two important details of the way it is constructed:

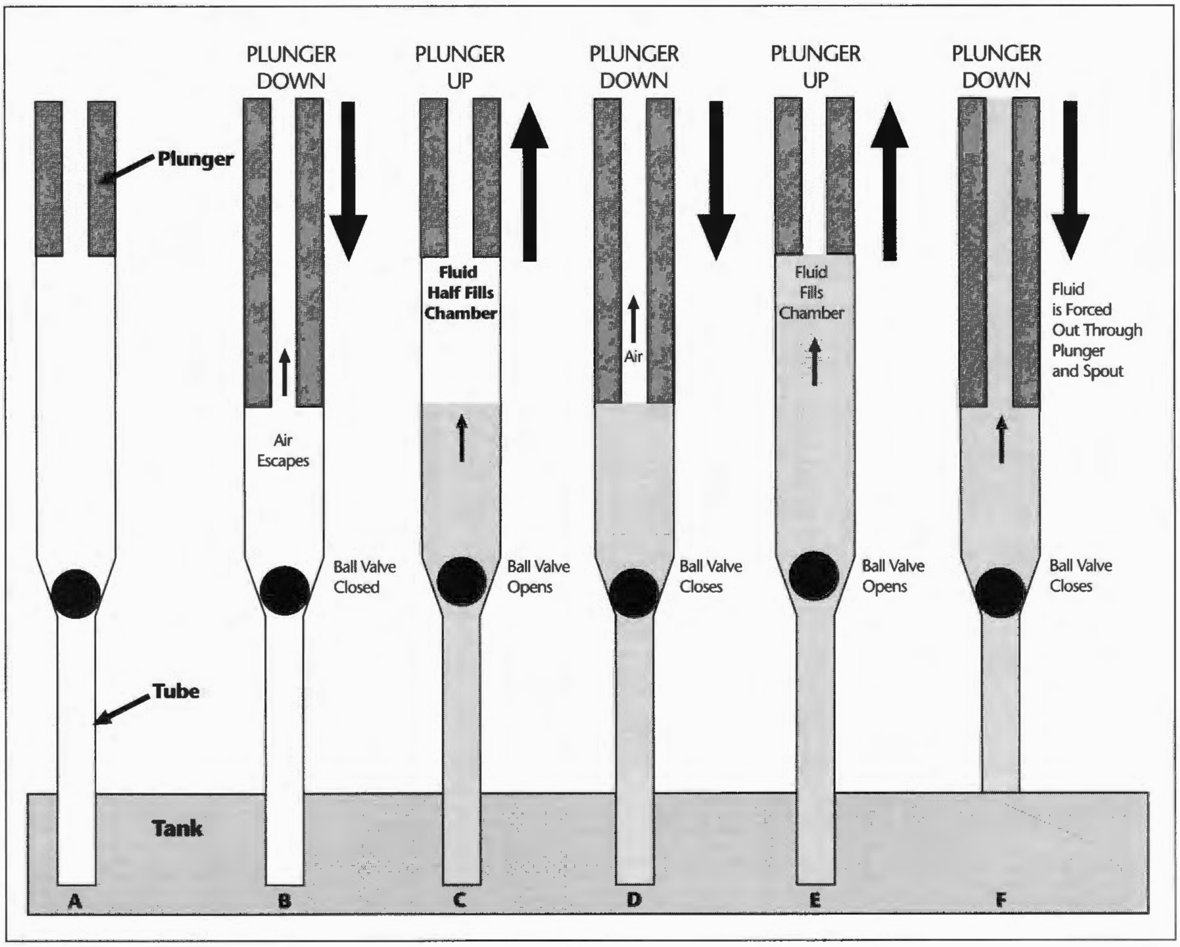
1. **The plunger is hollow** (Figure A-22A). This allows fluid to pass through it when it is pushed down.
2. **A little ball bearing is held in a little space between the chamber and the tube that goes down into the tank of fluid** (Figure A-21). This little ball forms a one-way valve. which prevents air or liquid from ever passing downward from the chamber into the tank. Liquid can only pass upwards through the ball valve.

Based on this information, we can now explain all of the steps illustrated in Figure A-20. The six diagrams in Figure A-22, A through F, correspond to the photos in Figure A-20, A through F, respectively.

When you first push the plunger down (Figure A-22B), the ball valve closes, preventing air from passing into the tank. The valve closes because gravity keeps the ball down, closing off the opening into the tube. As a result, you will not notice any air bubbles in the tank, as you would if you pushed air into the fluid by blowing into a straw or squeezing an eyedropper. When the plunger is released, in C, the ball valve opens, because now the suction can lift the ball out of its seat. Therefore, the chamber partially fills with fluid. A similar sequence occurs during the second down stroke and up stroke, in D and E, respectively. At this point, the chamber has completely filled with fluid. The next down stroke, shown in F, forces the fluid through the hollow plunger and out the spout. It can't go back down into the tank, because the ball valve blocks it, so it can only go up, and it finally squirts out.

A-21: **Detail of pump dispenser, showing ball valve**

A-22: **How a pump dispenser works**



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This authoritative source has considerable material that is accessible to the non-technical reader. The articles on "Boxes, Corrugated," "Cartons, Folding," and "Closures, Bottle and Jar" are particularly useful.

Cassidy, John. (1985) ***Klutz Book of Knots.*** Palo Alto, CA: Klutz Press.

Knots are often the best way to join larger structural elements such as bamboo and rolled-up newspaper. Nearly anyone can learn to tie the most useful and common knots using this step-by-step, multicolor, humorously written guide. It comes with string and notches for practicing.

Fenichell, Steven. (1996) ***Plastic: The Making of a Synthetic Century.*** New York: HarperCollins Publishers.

Here is a popular account of the invention, uses, and consequences of the major plastic materials.

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This book offers an entertaining and often humorous account of how and why artificial and natural structures are organized the way they are. Gordon discusses how bats, trees, planes, ships, and dresses operate as structures.

Hanlon, Joseph F. (1984) ***Handbook of Package Engineering*** (2nd Edition). New York: McGraw-Hill Book Co.

This small book offers a wealth of information, much of it non-technical, about packaging materials and manufacturing technologies.

Henessey, James and Papanek, Victor. (1975) ***Nomadic Furniture 1.*** New York: Pantheon Books.

This book shows you how to make temporary or easily movable furniture, some of it from recycled materials.

Hine, Thomas. (1995) ***The Total Package: The Evolution and Secret Meanings of Boxes, Bottles, Cans and Tubes.*** Boston: Little, Brown and Co.

Hine provides a history of modern packaging, and shows how it has evolved together with changes in society. It includes beautiful photos of packages from an earlier era. The focus is primarily on the promotional aspects of packaging.

Kluger-Bell, Barry. (1995) ***The Exploratorium Guide to Scale and Structure: Activities for the Elementary Classroom.*** Portsmouth, NH: Heinemann.

This is a carefully thought-out, well-sequenced curriculum on structures for the upper elementary grades. It includes a brief but very accessible section on science and engineering principles, a wealth of activities, teacher tips and connections with standards. All of the activities use common materials.

Mumford, Lewis. (1967) ***Technics and Human Development: The Myth of the Machine, Volume 1.*** New York: Harcourt Brace Jovanovich.

This classic interpretation of the origins of technology emphasizes the role of language and art, far more than most accounts. It also criticizes the male bias in most histories of technology.

Package Design in Japan. (1993) Cologne, Germany: Taschen.

This gorgeous book shows examples of how the Japanese think about packaging. Every package in this book is a work of art, intended to have at least as much value as the contents.

Paine, F. A., ed. (1991) ***The Packaging User's Handbook.*** New York: Van Nostrand Reinhold.

Here is a fairly non-technical compendium of information about all the major problems in packaging. The chapters on "Closures and Dispensing Devices" and "Package Cushioning Systems" are particularly useful.

Petroski, Henry. (1992) ***To Engineer Is Human: The Role of Failure in Successful Design.*** New York: Vintage Books.

Petroski uses examples from the history of structural engineering to show how design progresses via analysis of past failures. The author suggests experiments with everyday objects like kitchen knives and paper clips.

Petroski, Henry. (1996) ***Invention by Design.*** Cambridge, MA: Harvard University Press.

Chapter 5, "Aluminum Cans and Failure" provides a brief history of beverage cans, and dicusses the invention of the pop-top in detail.

Roth, Laszlo and Wybenga, George L. (1991) ***The Packaging Designer's Book of Patterns.*** New York: Van Nostrand Reinhold.

This book contains hundreds of drawings, showing the flattened and assembled views of a wide variety of folding boxes. It also contains some technical information on cardboard.

Salvadori, Mario and Tempel, Michael. (1983) ***Architecture and Engineering: An Illustrated Teacher's Manual on Why Buildings Stand Up.*** New York: New York Academy of Sciences.

Some 70 lessons, aimed at junior high school and high school levels, describe step-by-step how to build and test structures from everyday materials.

Salvadori, Mario. (1990) ***Why Buildings Stand Up: The Strength of Architecture.*** New York: W. W. Norton.

This classic is a very readable account of how structures support loads, and why they sometimes fail to. It provides clear explanations of compression, tension and shear, and describes major structural elements, such as arches, columns and beams.

Schools Council 5/13 Series. (1982) ***Structures and Forces: Stages 1 and 2.*** London: MacDonald Educational.

This excellent volume is full of ideas about how children can observe and experiment with structures. There are excellent examples of investigations designed by children, as well as ideas for making and testing structures using common materials.

Vogel, Steven. (1998) ***Cats' Paws and Catapults.*** New York: Norton.

Vogel, a biologist, has written a clear, comprehensive account of the major differences between the mechanical worlds of nature and technology. Chapters 4 through 7 deal with structures.

Wilson, Forrest. (1989) ***What It Feels Like to Be a Building.*** Washington: Preservation Press.

This unique book has very few words, but many, many pictures, and is suitable for all levels. There are drawings of famous structures next to silhouettes of people supporting each other in the same way as these structures.

Zubrowski, Bernie. (1993) ***Structures.*** White Plains, NY: Cuisenaire Co.

This compact guide provides instructions for building and testing a variety of straw structures: a house, a column, a bridge and a tower. Although the activities are intended for grades 5-8, the book is an excellent resource for all grade levels.

Chapter 6

American Association for the Advancement of Science. (1989) ***Science for All Americans: A Project 2061 Report on Literacy Goals in Science, Mathematics and Technology.*** Washington, DC: Author.

American Association for the Advancement of Science. (1993) ***Benchmarks for Science Literacy.*** New York: Oxford University Press.

American Association for the Advancement of Science. (1997) ***Resources for Science Literacy.*** New York: Oxford University Press.

American Association for the Advancement of Science. (1998) ***Blueprints for Reform.*** New York: Oxford University Press.

American Association for the Advancement of Science. (2001) ***Designs for Science Literacy.*** New York: Oxford University Press.

International Technology Education Association. (1996) ***Technology for All Americans: A Rationale and Structure or the Study of Technology.*** Reston, VA: Author.

International Technology Education Association. (2000) ***Standards for Technological Literacy: Content for the Study of Technology.*** Reston, VA: Author.

National Center on Education and the Economy. (1997) ***New Standards Performance Standards; Vol 1: Elementary School.*** Washington, DC: Author.

National Council of Teachers of English & International Reading Association. (1996) ***Standards for the English Language Arts.*** Urbana, IL: Author.

National Council of Teachers of Mathematics. (1989) ***Curriculum and Evaluation Standards for School Mathematics.*** Reston, VA: Author.

National Council of Teachers of Mathematics. (2000) ***Principles and Standards for School Mathematics.*** Reston, VA: Author.

National Research Council. (1996) ***National Science Education Standards.*** Washington, DC: National Academy Press.

GLOSSARY

Arch: A rounded structure that supports loads largely in compression.

Beam: A horizontal building element.

Box certificate: A standard label printed on a cardboard carton with information for shippers and freight handlers about the characteristics of the cardboard.

Buckling: Failure of a column by bending near the middle.

Column: A vertical building element, designed to resist compressive loads.

Compression: The state of a material made more compact by pressure.

Compression structure: A structure that supports loads by resisting compression.

Corrugated: Having a wavy shape; also, a name for cardboard that has a wavy layer in between two flat layers.

Dead load: The weight of a structure itself, not including the load it is intended to support (see *live load*).

Dome: A cylindrical structure, rounded at the top, which is the equivalent of having an arch in every direction.

Equilibrium: A balance of forces, which keeps an element from moving.

Facing: One of the two flat sides of a piece of corrugated cardboard.

Failure: Situation that occurs when a structure can no longer resist the loads it is subjected to.

Forces: Pushes or pulls on objects.

I-beam: A structural member, whose cross-section looks like the capital letter "I."

Inclined plane: A ramp used to lessen the amount of force needed by increasing the distance over which a load must travel.

Live load: The weight of anything supported by a structure.

Load: A force, such as gravity, that a structure must withstand in order not to fail.

Mechanism: A device with moving parts that converts force and motion at one point to a different combination of force and motion at another point.

Medium: The corrugated middle layer of a piece of corrugated cardboard.

Packaging: Material used to contain, protect, and make it easier to transport an item.

Recycling number: A number from one to seven that appears on the bottom of a plastic container.

Shear: State of a material that is acted upon by off-center forces; for example, the forces on a deck of cards when you press your hand across the top of the deck.

Shear resistance: Ability of a material to resist shear forces.

Simple machine: One of several elementary machines once considered to be the elements of which all machines are composed: the lever, the wheel-and-axle, the pulley, the inclined plane, the wedge, and the screw.

Splaying: Failure of columns to remain vertical by spreading or slipping outward.

Stability: The capacity of an object to return to its original position after having been displaced.

Strength: Resistance to failure.

Structure: A device or system designed to withstand a load.

System: The arrangement or interrelation of all of the parts of a whole.

Strut: A structural element, such as a column, intended to resist compression.

Technology: The artifacts, systems, and environments designed by people to improve their lives.

Tension: The state of a material produced by the pull of forces, tending to cause it to extend.

Tension resistance: Ability of a material to resist being extended, without breaking or stretching irreversibly.

Tie: A structural element designed to resist tension, such as a fishing line.

Viscosity: The property of a fluid that describes the difficulty encountered in making it flow.