Know When to Fold

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In the woods of Snoqualmie there's a tale that is told
When the day times are balmy and the night stars turn cold,
Of a bear that roamed freely, making camp sites a wreck,
Thwarting trappers from Greely, New Orleans, and Quebec.
'Til a gal with red hair and a trained 3D brain
Said, "I'll capture that bear in a folded-up plane."
She cut and she scored, and made a sight to behold:
An old sheet of board that was ready to fold.
When the job was complete, she made bait from old fish.
The bear thought it smelled sweet: "Les Poissons! Très delish!"
Then sproing, slip, and slap! As quick as a fox
She flipped the last flap, and caught the bear in the box.
They set the bear free, far north in the wood,
Where he let campers be and ne'er again ate their food.
The lesson we've learned is to question brute force,

And you've no doubt discerned that somehow I had to work in some sort of reference to this month's topic of cardboard boxes, and though this whole bear story was a bit implausible, it did the job, though I did have to stretch—just a little, of course.

Boxes made of corrugated cardboard are ubiquitous, but often overlooked. Some boxes are remarkable because they're made of a single piece of cardboard, which is neither glued nor taped. Yet they're capable of great strength, rigidity, and longevity—protecting fragile items during international shipping or holding a set of favorite pens and pencils for many years.

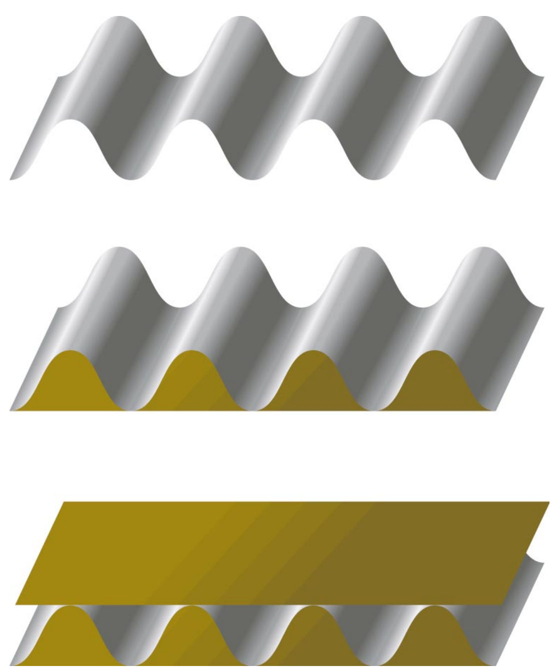
In this column I'll share a few box designs and talk a little about how I like to think about them. My goal is not so much to present specific boxes, but to get your 3D visualization skills fired up. Once you make the models and play with them and start thinking about where the pieces fold and where the clearances should be, then you can start seeing the entire shape in your head. The simple 2D layout transforms into an imminent 3D object: the template seems to want to jump up and fold itself up into a box, and you can see in your mind's eye just how cleanly everything fits and how strong and stable the result will be.

A long time ago . . .

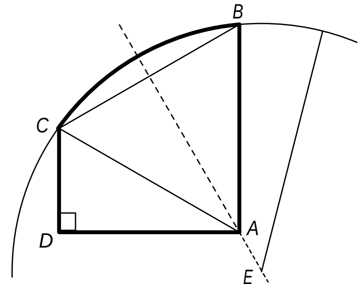
A relatively recent invention, corrugated cardboard began life as something called *fluted medium*. This is simply paper shaped into an extruded sine wave, shown in Figure 1 (top). Fluted medium was originally used as a sweatband in men's hats. I suspect that this had two advantages. First, the crinkled paper could flex a little bit, thus ensuring a snug and comfortable fit for slightly different head shapes and sizes. Second, like a fractal, this design increased the available surface area so that the ring could absorb more sweat than a simple band.

In 1871, Albert L. Johnes received a patent on using fluted medium to protect bottles when they were shipped and stored. One drawback to fluted medium at this point was that with enough pressure, it could flatten out again and lose its shock-absorbing abilities.

This changed in 1874, when Oliver Long received a patent for gluing a sheet of paperboard to both sides of the fluted medium, creating the corrugated cardboard we know today. The paper served to keep the fluted medium curved, maintaining its ability to absorb shock.



1 Making corrugated cardboard. Fluted medium (top). Single-face corrugated board (middle). Double-face or single-wall corrugated board (bottom).



2 The geometry of a flap of the hexagonal envelope. Equilateral triangle *ABC* sits next to 30-60-90 triangle *ADC*. *E* is the center of a circle that lies anywhere on the line joining *A* and the bisector of side *BC*. When *E* is chosen, the radius is determined by the distance to *B* (or *C*). The heavy line shows the flap.

Today we call the original fluted medium *unlined*. With a paperboard liner on one side (as in Figure 1b) it's called *single-face corrugated board*. The most common variety is covered on both sides (see Figure 1c) and called *double-face* or *single-wall corrugated board*.

The idea of selling individual products in their own package directly to the individual came a few years later. In 1879, Brooklyn printer and packaging material manufacturer Robert Gair was overseeing a press run of seed packets. One of the printing plates was placed on the press incorrectly and ended up slicing a package. While looking at the ripped package, Gair had the idea of replacing the printing plates with cutting plates and the die-cut package was born.

It first hit the shelves in 1896, when the National Biscuit Company started selling Uneeda Crackers in their own boxes (along with an inner sleeve to retard spoiling). As little as 25 years later, the US alone had hundreds of cardboard-carton manufacturers.

Designing a cardboard box is not trivial work: it requires balancing aesthetic demands and practical efficiency. A designer needs to wield a relatively small set of design techniques with the imagination to come up with an economical, practical, and attractive design.

When designers want to show a proposed box to a client, they prepare a *cutter diagram*—a drawing of the unfolded box's layout showing where cuts should be made, pieces punched out, and folds scored (along with the direction of the fold).

The conventions for these diagrams are very much like those in origami (the art of paper folding). A solid line indicates a cut, a dotted line means the pieces on both sides of the fold are pushed away from you (creating a mountain), and a line of alternating dashes and dots means the pieces are folded up towards you (creating a valley).

From the cutter diagram the designer makes a blank, or a plain cardboard mock-up of the design. If the client approves, the artwork is designed and registered to the box.

The blanks are generally created in one of three ways. First, you can shape a piece of metal into the desired outline of the box and use it like a cookie cutter to stamp the box from the cardboard sheet. This is called *hollow die cutting*, which manufacturers use exclusively for labels and envelopes.

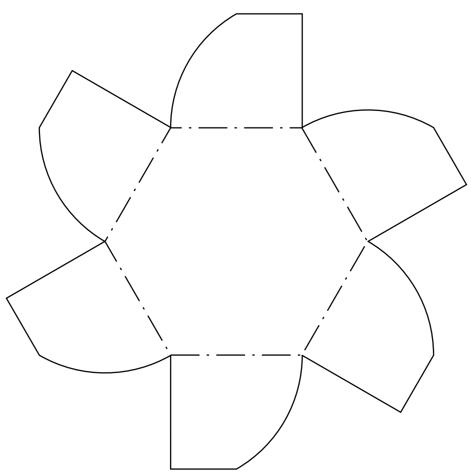
Second, you can shape one or more metal steel rules into shape and then push them into precut grooves in a piece of 3/4-inch plywood. This technique of *steel-rule die cutting* can be used with both flat and cylindrical presses. If the steel rule is blunted, then it can be used to press grooves and thereby score folds. This is by far the most common technique.

A recent innovation is *laser cutting*. The advantage here is efficiency and accuracy, though it's used less often than steel-rule die cutting.

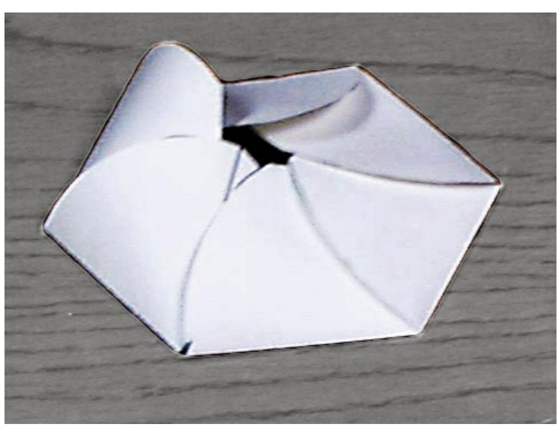
Once cut and scored, the blanks are delivered to the client in knock-down form, which simply means that they're flat but ready for assembly. This involves folding and perhaps gluing, taping, and adding extra pieces such as rubber bands or springs.

When experimenting with designs (as opposed to mass producing them), I find that a metal straightedge and X-Acto knife work fine for making cuts. You can use an empty ballpoint pen for scoring, but be careful not to rip through the paperboard.

You can make many cutter diagrams with traditional tools such as a straightedge, ruler, compass, calipers, and so on. I find that although there's a certain aesthetic appeal to the paper-and-pencil route, I can work a lot more quickly on the computer using an off-the-shelf 2D drafting program. Then it's easy to make a design variation, which can be printed, rubber-cemented to a piece of manila folder, and then cut and scored. One iteration of the loop from printing the diagram to holding the final box takes only about 15 minutes for the boxes I describe here.



3 The cutter diagram for the hexagonal envelope.



4 The hexagonal envelope made from a manila folder.

Hexagonal envelope

Before we get into major 3D mental-visual calisthenics, let's warm up with a simple workout: a flat hexagonal envelope. This is made from light board such as a manila folder. Because this material is quite thin, you can pretty much treat it as infinitely thin when designing the diagram and things will still line up closely. This envelope should contain something thin and small, such as a party invitation, photograph, or blueberry pancake.

Figure 2 shows the geometry behind one flap of the top of the envelope. Figure 3 shows the template for the entire hexagonal envelope, and Figure 4 shows the result. The top stays closed because the curved bit on the side of each triangle holds down its neighbor. Since the lid is circular, each flap simultaneously contributes both to the tension pulling the envelope open and to the mutual pressure keeping it closed.

In Figure 5 I added walls to create a squat hexagonal box, but the principle remains the same. The triangular flaps tuck inside their neighbor to prevent cracks at the edges. You could still use manila folders for a short box, but corrugated cardboard would be better for a tall one. This is a good box for collections of things such as buttons, rubber bands, or stacks of blueberry pancakes.

Construction techniques

Now we're ready to get into thicker, stronger materials such as corrugated cardboard. I'm not an expert in this subject. I don't have any first-hand knowledge of how these boxes are professionally designed and built. But from examining a lot of boxes and playing with them, I've recognized a few techniques that appear over and over. The description of the boxes will be much easier if I cover these techniques first.

To see them, let's start with a simple cube. Figure 6 shows one of many possible cutter diagrams for the six square faces. To build a cube from this you'll need to tape the edges, since it can't hold together by itself. And even then it will be structurally weak and prone to wobbling and crushing.

For practical use, you'll want to improve two things about this cube. First, it should be stronger, so anything placed inside (such as a cream puff) won't be squashed. Second, it should be more rigid or stable, so that it doesn't wobble. These two properties of a strong box are closely related, but before passing judgment on a design, you should check it for both criteria.

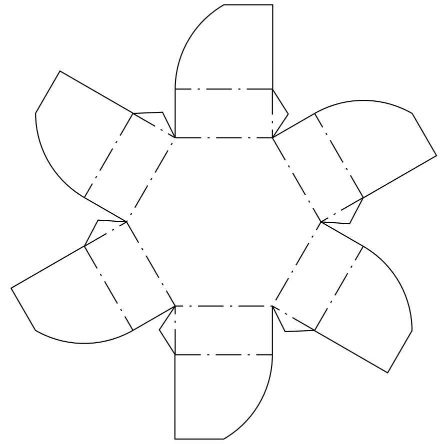
Let's now look at some techniques for improving this simple box.

Flaps and locking

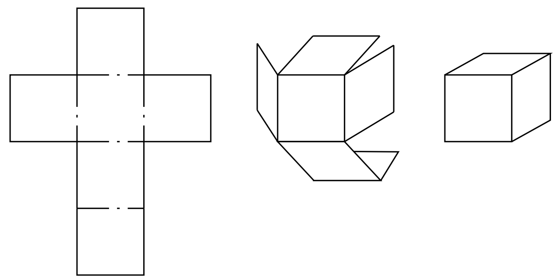
One of the most elegant answers to both strength and rigidity is the use of *flaps*. Flaps can be used to create walls several layers thick, which strengthens them. And the flaps hold other flaps in place, keeping the structure in its designed shape. You can use flaps in all sorts of way to do these jobs, but they all have something in common: somewhere, something has to lock into place.

Figure 7 shows one approach using a tab and a hole: a flap has a tab at the end and that end goes into a hole. The tab doesn't come out the other side—it's only as long as the cardboard is thick. The only pressure on the tab is sideways, which pushes it against the side of the hole. The rest of the box is usually arranged to keep the tab in the slot when the box is closed.

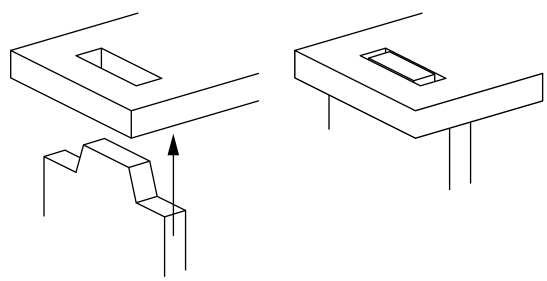
Figure 8 shows a cheaper version of the same device, except in this case you don't even make the hole. The flap is shorter and the tab pushes against the board where a hole would be. If you make the tab slightly too



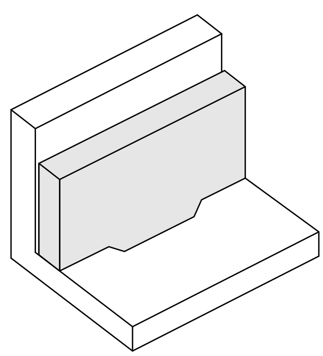
5 **The cutter diagram for the hexagonal box.**



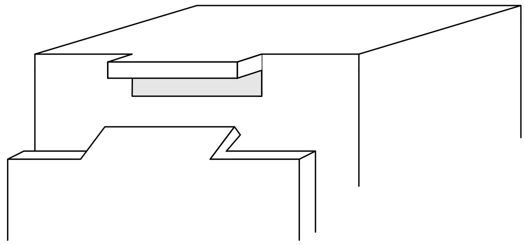
6 **A cubical box. The cutter diagram (left). Folding it up (middle). The resulting box, which will only hold together if taped or glued (right).**



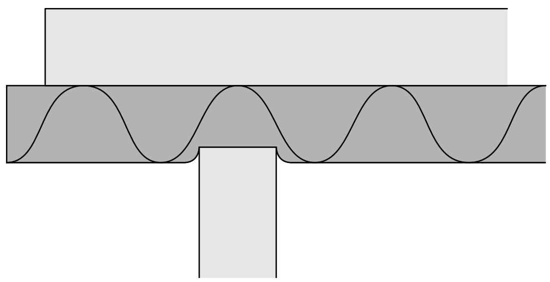
7 **The tab fits into the hole (left), but doesn't extend out the other side (right).**



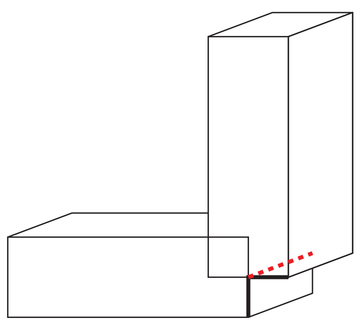
8 **The gray piece has a short tab on the bottom, which is crushed against the bottom wall.**



9 **The tab fits into the slot along the edge.**



10 **The lower lip of the slot (light gray) pinches the tab (dark gray), holding it securely in place.**



11 **The fold is modeled as though two separate pieces of cardboard shared a centered hinge.**

long to fit in the box, you can jam the tab down into the board (it will crush a little). The pressure will keep the tab from sliding around. This is weaker than using a slot, but can be cheaper to manufacture (since you don't have to cut a hole). You can make this device stronger on a long edge by using several tabs side-by-side.

Another useful device keeps the box shut. Figure 9 shows the idea: a tab on the front face pushes into a hole in the edge between the top and inside front faces. If the cardboard is just a little thicker than the hole, it will be squeezed a little by the bottom edge of the hole against the top. If the cardboard's grain is parallel to the hole, then you can move the bottom piece into the dips of the inner corrugated layer, as in Figure 10. This friction helps keep the tab in place and keeps the top closed. A U-cut in the tab creates the smaller piece that you grip to pull the larger tab out. As you'll see with the shoe box below, a particularly elegant touch is that the hole is cut so that the top face protrudes a little forward (this gives you something to grip with your thumb when pulling the top of the box open).

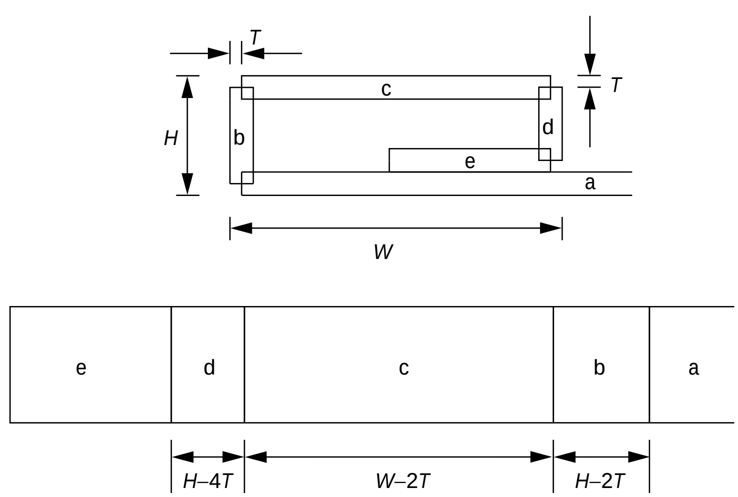
Parameterization

The cardboard's thickness is imperative to the success of tabs. The tab technique doesn't do you much good with a thin card because there's nothing for the tab to push against. The size of any locking device (tab or hole) needs to match the card's thickness.

Thus we're naturally led to parameterizing the templates, which is a good idea anyway. All of the template sizes should be with respect to the four numbers that describe the box. These are length L, width W, depth D, and thickness T. I found it convenient to define T as one-half the thickness of the board, thus a sheet of cardboard has a thickness of $2T$.

The box's measurements are with respect to its outermost dimensions, including the cardboard's thickness. So if someone says that they have a hole in a piece of concrete with dimensions L, W, and D, then a box made with those numbers will fit in the hole exactly.

Naturally, this isn't perfectly true in practice. The big question is what happens when the board folds. I spent some time folding corrugated cardboard and watching what happens and came up with the model in Figure 11. Basically, I assume that the board folds around a hinge in the middle of the card. The paper on the inside of the hinge compresses, and the paper on the outside stretches (I omitted the paper in this figure for clarity). This is obviously an approximation, but it seems to fit what I



12 **A U-fold as part of a wrapped-up tube (top). If the total width is *W*, the distance between fold lines for section c is *W* – 2*T* (bottom).**

see when I fold a sheet. Plus, it matches the way most boxes seem to be cut when I open them up and measure the pieces.

Figure 12 shows how to analyze a U-fold (such as at the bottom of a box). The rule of thumb is that at a 90-degree fold, the folded cardboard sticks out a distance *T* beyond the base (and extends *T* inwards as well). So if the base is meant to be *W* units wide, the fold lines are drawn a distance of $W - 2T$ apart. When the ends are folded upwards the distance *T* sticking out on both sides brings the total width to *W*. This is why I use *T* for the half thickness of the cardboard and 2*T* for the full thickness.

Idioms

We've already seen one common feature of corrugated boxes: folds extend *T* units over their base. Another common idiom is the 3D corner.

The top left of Figure 13 shows the corner of a box, and the top right shows how to analyze the construction. Notice two features. First, the bottom of b is above the bottom of a. This is because c folds around hinge AC and will extend *T* units above the hinge line. Thus b must be cut short by *T* units. Similarly, the side of c must be wider than a so it can line up with b. So c extends beyond a by *T* units. The bottom left of Figure 13 shows how this looks in a diagram. The little notch is a characteristic feature of many corners.

You can cheat sometimes and leave the notch out. The safest place to do this is if one of the sides is a flap and not outside the box. Then it will scrunch up against the other piece, which can provide it with a little side-to-side strengthening.

Lock box

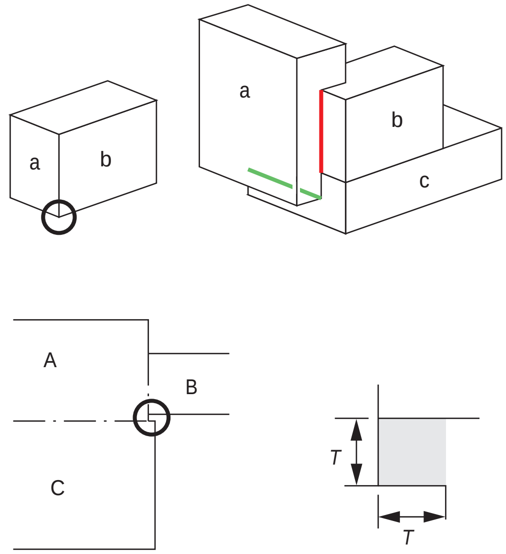
Figure 14 shows what I call a "lock box" because it locks up tight. I got this design from a box full of books that I recently received in the mail. I knew it had to be very reliable if it was going to carry such precious cargo without damage. I took the box apart and studied it, resulting in the diagram in Figure 15. I labeled some spots in Figure 15—the other half of the diagram is symmetrical (as such templates often are).

The first trick is set up by the side flap f. When folded in, it provides another layer of thickness against wall h, strengthening it and keeping it from moving. The payoff comes with the flap made of p and r. On the outside, p pops up, which is fine. Then the little bit between them rolls over the top and r goes back down inside, locking into the base with a tab.

This is a huge win in stability and strength. With this trick the designer quadrupled the thickness of the side wall, making it strong and stable. This technique also added stability to the front and back sides s and t, because now they can't rotate around their hinges.

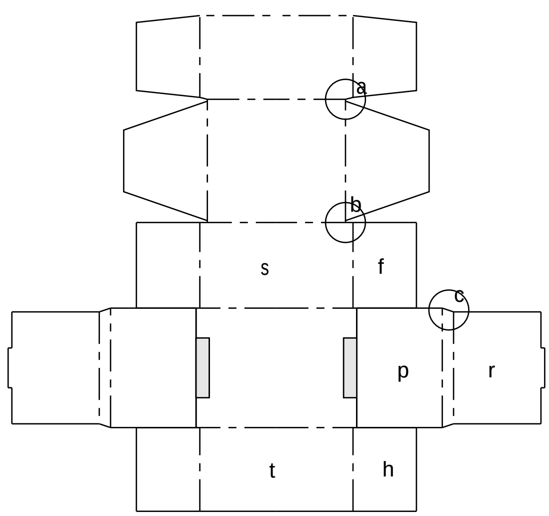
As if this weren't enough, the top fits inside this thick wall and adds a fifth layer. Then the front tucks into the front of the wall, reinforcing the corner against dents while adding a sixth layer to the wall (though it only covers a bit of the wall). Having the real box to work on helps enormously in figuring out the parameterizations and hinge axes.

I made special note of three interesting spots marked



13 **A corner fold. The corner of a box (top left). A close-up of the fold (top right). The diagram for the corner (bottom left). A close-up of the circled region in the diagram (bottom right).**

14 **A photo of a lock box.**



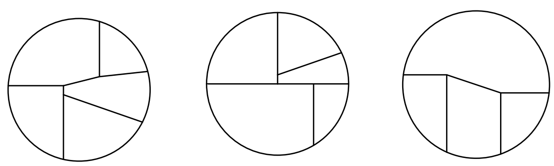
15 **The diagram for the lock box.**

a, b, and c (enlarged in Figure 16). Note the extra clearance in the notches of thickness T in a and b and how the width of flap r is reduced by $2T$ in c. I originally wrote a few paragraphs to explain these details, but decided this is one case where experience is worth a thousand explanations. I highly encourage you to build this box (or disassemble one like it) and see for yourself why these little adjustments aren't just useful, but elegant.

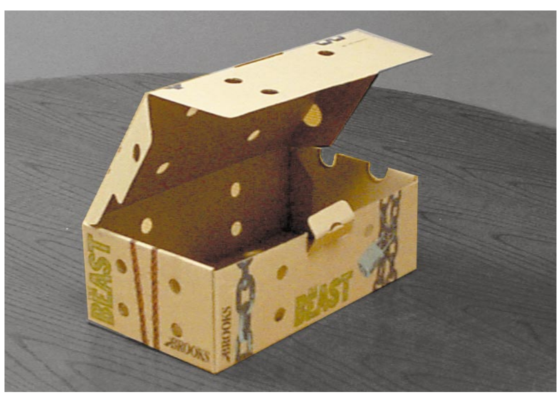
Shoe box

I bought some new sneakers last week and selected one model in particular because they were tough and strong. The manufacturer played off this reputation by printing locks and chains on the shoe box and adding air holes, as though what was inside was alive and so powerful it required that kind of restraint to keep it contained. Wow, that's a lot of promise for a sneaker.

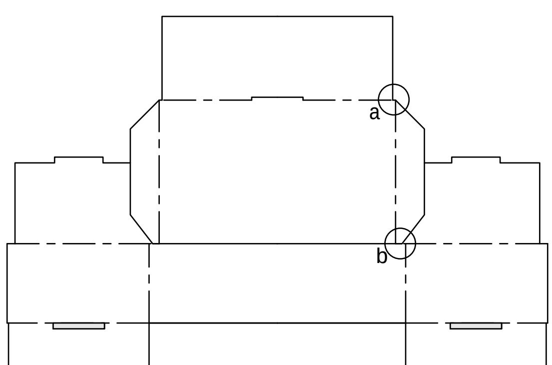
The package would be a joke if it were made of flimsy, thin board. This shoe box is solid and contributes to the notion of something strong inside. I squeezed hard on the walls of this box—it didn't buckle or give. Figures 17 and 18 show a photo and a diagram of the shoe box, respectively.



16 **Close-ups of regions a, b, and c in Figure 15.**



17 **A photo of a shoe box.**



18 **The diagram for the shoe box.**

This shoe box's strength starts with a medium-thickness board (about 3 mm). It uses a couple of variations on the lock box trick. The side flaps reinforce the base rather than the sides, but then other flaps make the side triple thick. The shoe box also has a tab and a slot to keep the sandwich on the side together. The front flap doesn't tuck into the front as we saw before. Instead, there's a flap that sticks into a slot in the top front. This is very important. If this additional locking device had not been included, then the top would stay on only as a friction fit, and the dangerous sneakers could escape at any time.

Again, I noted three interesting details in the diagram and enlarged them in Figure 19. If you build the box you may be as impressed as I was with how the designer made the right adjustments in the right places.

Display easel

Figure 20 shows a nice example of a display made out of corrugated board. This little display easel is made from a single sheet, yet it provides a stand with thickness (for many sheets of paper or a thin product), a short base, and a solid, locking support. See Figure 21 for the diagram.

CD-ROM package

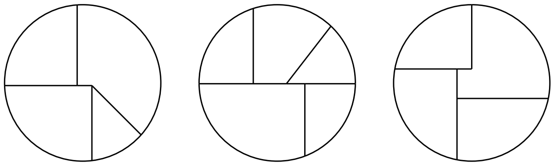
A lot of software is sold today on CD-ROM. But CD-ROMs are pretty small, and I've gotten the feeling that manufacturers like to sell things in big boxes—it implies that you're getting a lot of stuff for your money. So they include some documentation, a registration card, and perhaps advertisements for other products. Now they have the problem of keeping the CD-ROM from flopping around in the much larger box.

Typically designers create a bright, eye-catching cardboard sleeve around a corrugated sheet that cradles the CD-ROM and keeps the documentation together. Figure 22 shows an example. Figure 23 shows the diagram.

I included this example because it's so elegant. The CD is held safely in the middle of the box—protected and buffered on all sides—and the printed materials are all kept in their own compartment. The down side of this design is that it's wasteful—the package could be much smaller and use less material. I'm guessing that marketers and retailers have a minimum-sized package in mind, large enough to contain arresting graphics and to suggest that it's full of good stuff. Although the CD holds a huge amount of data, it's pretty small. I presume that a bigger box makes it look more impressive.

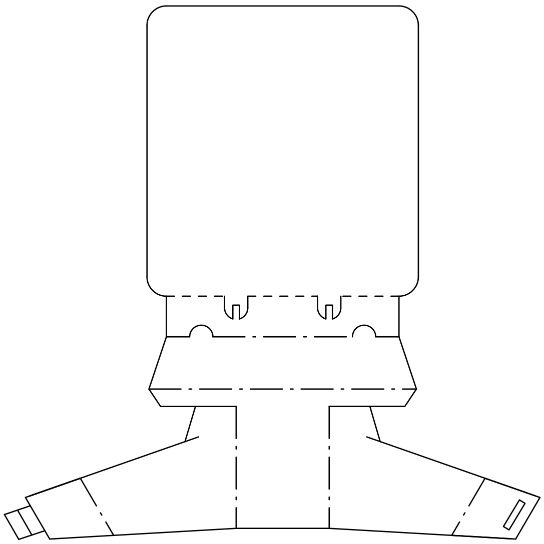
Folding up

I encourage you to build the models, play with the pieces, and try out variations. Or disassemble some boxes on your own and see how they're built. You can find some good advice for making boxes in *Card Engineering* by Ian Honeybone (Outline Press, London, 1990). The hexagonal box in this column was taken from that book. Most of the history section (excluding my conjectures) came from *The Packaging Designer's*



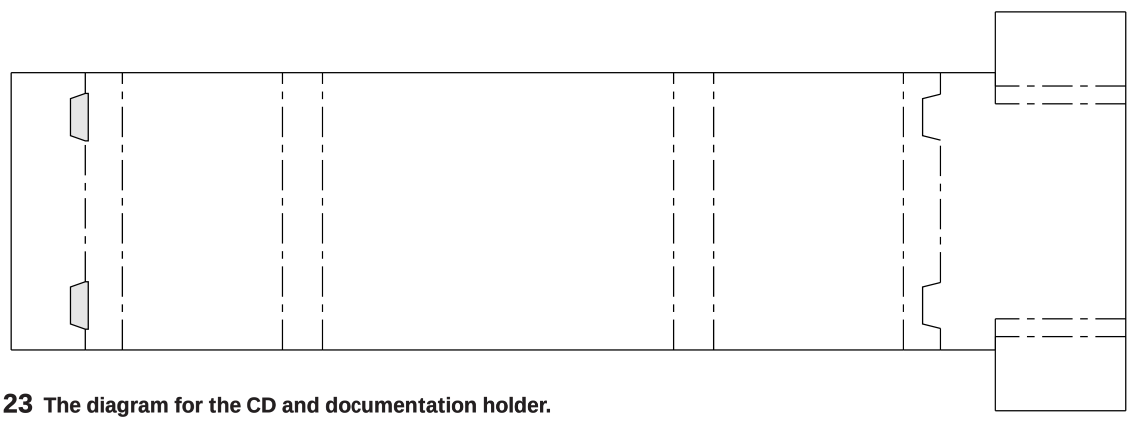
19 **Close-ups of regions a, b, and c in Figure 18.**

20 **A photo of an easel display.**



21 **The diagram for the easel.**

22 **A partially folded CD and documentation holder.**



23 **The diagram for the CD and documentation holder.**

Book of Patterns by Lászlo Roth and George L. Wybenga (Van Nostrand Reinhold, New York, 1991).

I recommend starting out with a thin card for your designs until you get the hang of things—it's easier to cut and quicker to try to out new ideas. Then you can go to double-sided corrugated cardboard for structures with a lot of strength, rigidity, and durability.

Last-second addition: Box knowledge can have great practical value. At Siggraph 98 in Orlando, Florida just a few weeks ago, Team Seattle (David Salesin, Michael Cohen, and me) won Siggraph Bowl III (a computer graphics trivia contest). We each received a first-place prize of an inscribed Luxo desk lamp. One of us opened up our box on the spot to admire it, only to discover when putting it away that the lamps had been creatively packed in tricky cardboard boxes. Only through our knowledge of boxes and packing techniques were we able to safely return the lamp to its original box and ship it back to Washington unharmed (where it can now sheds its light of triumphant victory through the rainy Seattle days and nights). ■

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