CHAPTER 13 - LET'S MAKE AN ARCH FROM CARDBOARD!

The cardboard arch or "bridge" project is a multi-faceted learning experience, whether done by a group of adults or students, with dramatic and very impressive results. What begins as a fascinating class-room exercise culminates in the construction of a cardboard bridge which spans a corridor, a room, or even a somewhat larger space, ranging in length from 16 feet to 30 feet or more, and rising to a keystone of 8 to 15 feet overhead! The smallest bridge I've ever made was a semi-circular arch about 16 feet from wall to wall, and the largest covered a span of 40 feet, with a keystone at 20 feet! In every instance, I can attest to the excitement this project generated among the students I worked with, as the "wobbly" arch took shape. And when the keystone was dropped into place and the whole construction "stood" all by itself, there was a burst of applause and the students cheered!

Objective:
Build an arch out of cardboard.

Vocabulary:
Arch
Keystone
Voussoirs

Materials:

For a smaller arch between 16 to 25 feet in length - approximately 25 sheets of 4' x 5' cardboard, 200 lb. card stock B or C flute, bleached on one side, single corrugation (Comes in 5' x 8' sheets, which the supplier can cut in half for you. "Bleached" means that one face is white, which is ideal if you want to paint or decorate the finished arch).

For a larger arch, 25 feet or more - approximately 50 5 x 8-foot sheets of 200 lb. double-wall cardboard. (This may not be available in "bleached.")

Four or five rolls of 2-inch wide clear cellophane tape

Several pairs of scissors

Long metal straightedges

Several sharp utility knives (Adults should be entrusted with the task of cutting)

Pencils

Paper (including graph-paper for the design phase)

Compasses

Rulers

Tape measure

Poster-board

Length of twine or wire

Choose a convenient, wide-open space where you want to construct and install the finished arch. Measure the distance between the walls, and the height of the ceiling. The

walls should be free of any obstructions, meeting the floor on each side at a perfect right angle. No heating vents, radiators, or air-conditioning ductwork should be in the way.

If the ceiling height is more than half the width of the space, you can build a full semi-circular arch, unless the space between the walls is extremely wide. In this case, the keystone of the arch would be too high for anyone to reach it during the process of assembly. A segmental arch would therefore be preferred. This is also true if the ceiling height is less than half the room width. Instructions for both are provided. Choose the type you are going to build, and refer to the appropriate section of this chapter.

Since all of our preliminary work will be done on graph-paper based on a scale, it is recommended that a smaller desk-top model made of poster-board only a foot or two in length is constructed first as a practice session. Once you have measured your large space, transfer the dimensions to a sheet of graph-paper, reduced to an appropriate scale (let's use 1/4-inch = six inches). The preliminary drawing should be a rectangle representing the floor (base line), walls, and ceiling, all drawn to scale. For our exercises we will use a 16-foot span with a 10-foot ceiling, which in the reduced scale comes to 8 inches by 5 inches. Once you learn the formula, you can adjust the arch size to your own specifications. Our arch will be about two feet thick (1 inch scale), and 30 inches (1 ½ inches) deep.

The Semicircular Arch

Steps:

1. There are several ways of designing a semicircular arch, from the very simple to the rather complex, the latter offering somewhat more fascinating possibilities. But let's start with a very simple design on poster board. Refer to **Figure 13.1**, in which the rectangle represents the 8 to 5 inch ratio described above, so you can use the pattern for a small or a large arch. From center point X on the base line spin a half-circle corner to corner (A to B), and another half-circle one inch inward (A' to B').

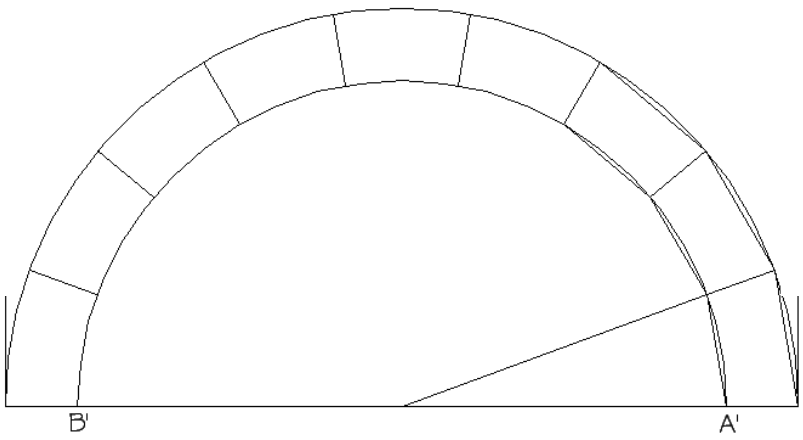

Figure 13.1

2. Now it would be easy to create a perpendicular to center point X, bisecting the circle into two equal sections, and then to continue bisecting the sections into four, or six, or eight equal sections, representing the individual arch "stones" or voussoirs. But we must remind ourselves that arches are made up of an odd number of voussoirs, in order to accommodate a central keystone at the crown. So how do we divide our arch into an odd number of identical voussoirs?

3. Easy. We use a protractor. We know that a semicircle consists of 180 degrees, so we must find an odd number by which 180 degrees can be divided with no inconvenient fractions. Three and 5 will work, but an arch of 3 or 5 voussoirs is hardly much of a challenge! Nine goes into 180 degrees 20 times, meaning that 9 voussoirs, each spanning 20 degrees of arc, would produce an attractive and meaningful arch. Even more so would be an arch of 15 voussoirs, each spanning only 12 degrees of the arc.

4. By placing a protractor on the base line of **Figure 13.1** centered on X, mark off the 9 voussoirs 20 degrees apart. You can then square off these voussoirs as we have done with the first few on the right side. Why square them off? Simply because straight cardboard cuts are much easier, faster, and more accurate. Also, cardboard doesn't bend very easily. However, poster-board does, and there is no reason why you can't have an attractive curved desk-top arch in poster board. We'll provide a template for this a little later on.

5. Once your design for the arch is complete, you may enlarge it on a copy machine or transfer it to a larger scale for actual construction. All you actually need is one voussoir pattern, separated from all the rest, since all copies will be exactly the same. Once you have done this, you must use this piece—actually a front panel—to design a kind of "box" which will become a three-dimensional voussoir. You must not only add a corresponding back panel, but a top, bottom, and two sides. A sketch is provided in **Figure 13.2a**, with a fully laid out net in **Figure 13.2b**.

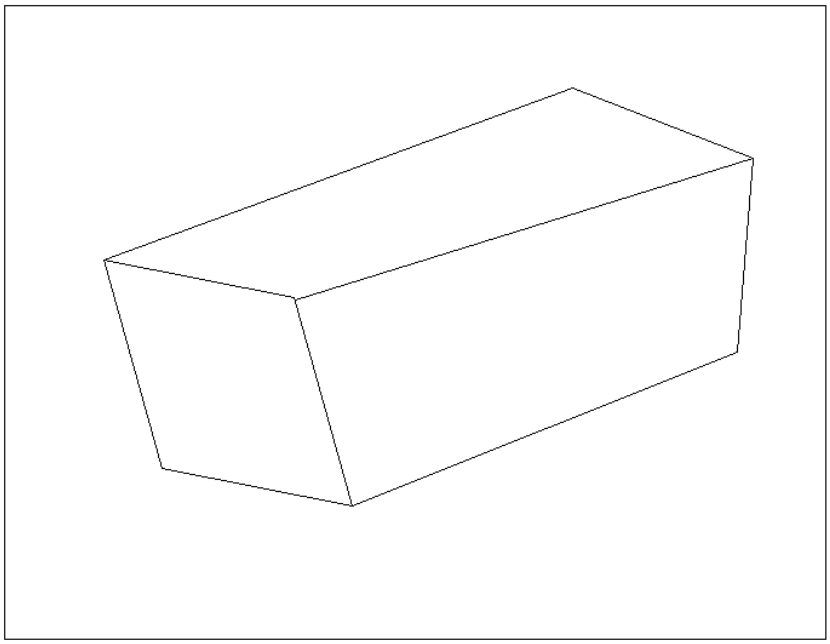

Figure 13.2a

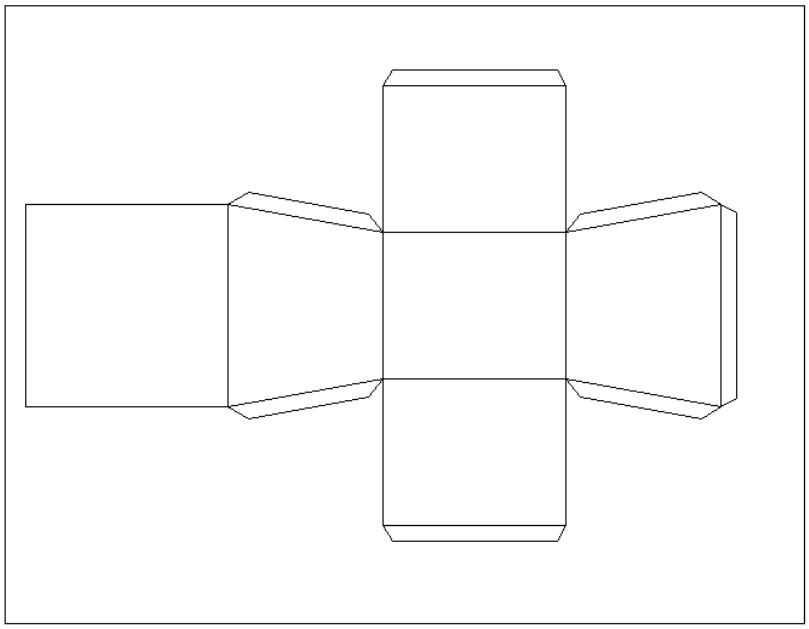

Figure 13.2b

6. We've given our voussoir a depth of 2 ½", which in large format would be about 2 ½'. For the sake of stability, it is always a good idea to make your arch somewhat wider (front to back measurement) than it is thick (top to bottom measurement). Our net has all glue tabs indicated. Make 9 of these to complete your arch. A word of advice, fill the two end-blocks with sand to give the arch the necessary support. Here's an interesting little "trick:" while your arch will hold together all by itself with no glue or tape, you might want to run a strip across the top connecting all the voussoirs—but not at the

bottom. Thus, you can "collapse" the arch flat by a little downward pressure. By pulling upward on the keystone, the arch will assume its original shape!

A Nine-unit Curved Arch

1. As promised, a net for one *curved* voussoir of a nine-unit arch is given in **Fig. 13.3.** The two shaded panels must be curved to fit the edge of the front and back panels, top and bottom, which account for the series of glue-tab "teeth". A straight glue tab would not allow them to take the curve.

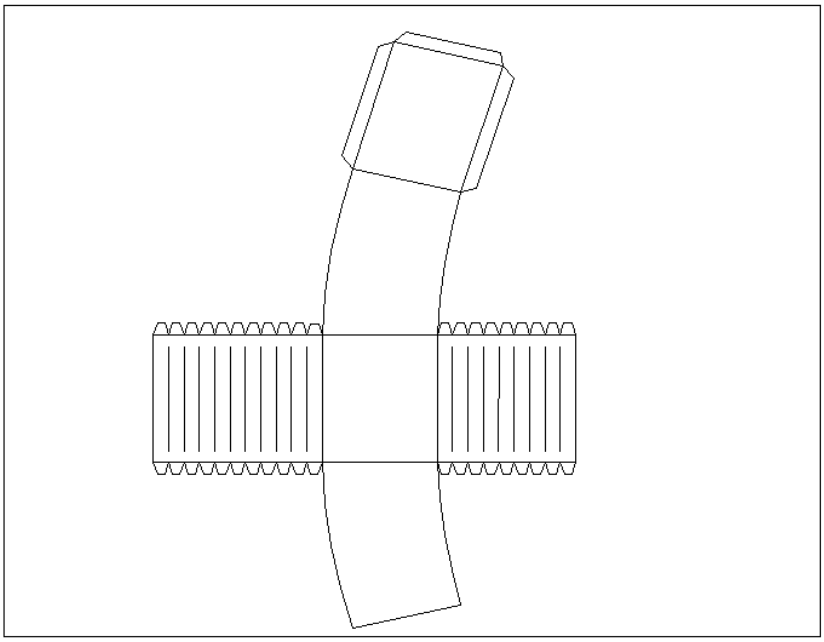

Figure 13.3

2. To construct a room-sized arch of this type, find the mid-point between the two walls, and tape down a piece of string from wall to wall as the base line. A large protractor at the center point will help you mark off the 20 degree spaces, which can be marked off on the floor using a long, straight stick or some heavy string as the compass. Actually, only one voussoir needs to be determined, since all will be identical. But just for the sake of accuracy, you might want to lay out the whole design.

3. With the shape of one voussoir panel, you have the template of all 9 units, plus the edge measurements of the remaining pieces needed for each box. All of these pieces—the top, bottom, and sides—should be 30 inches wide. Assemble the 9 units according to the net given in our figure, and put your arch together.

4. A 15-unit arch is only slightly more difficult, but the process is exactly the same. In this case, use your protractor to mark off divisions every 12 degrees, as we have shown in **Figure 13.4.** Each voussoir will be somewhat narrower in side view, but should be somewhat deeper front to back.

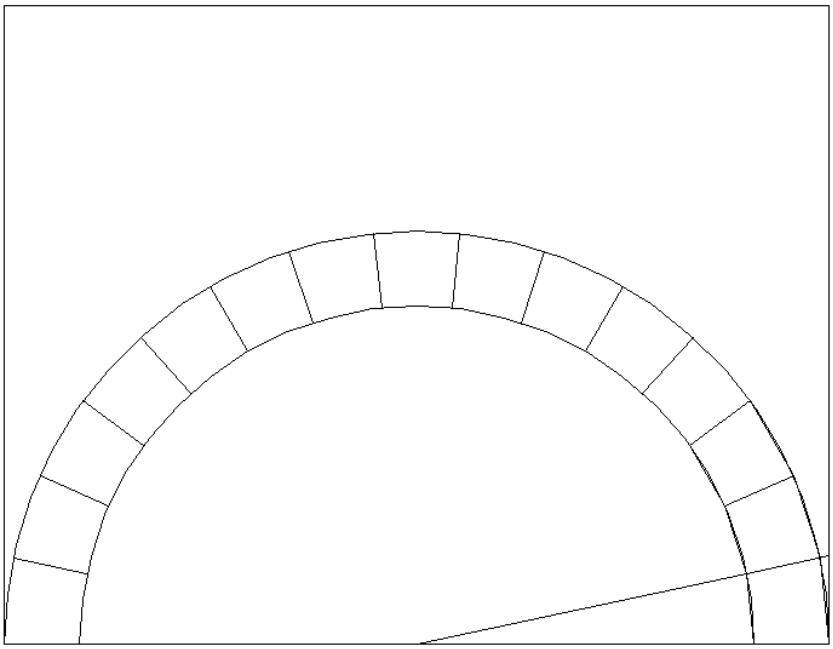

Figure 13.4

5. Another "easy" way to design an arch, this time without the use of a protractor, is to begin by arbitrarily designing the keystone to any practical size you desire. On line AB of **Figure 13.5**, simply sweep out the two half-circles as before, this time with a perpendicular indicated. Measure off the size of your keystone on each side of the perpendicular on the inner half-circle (C and D in **Figure 13.5**), and then mark off the edges of the keystone with lines to the center-point of the half-circle, X.

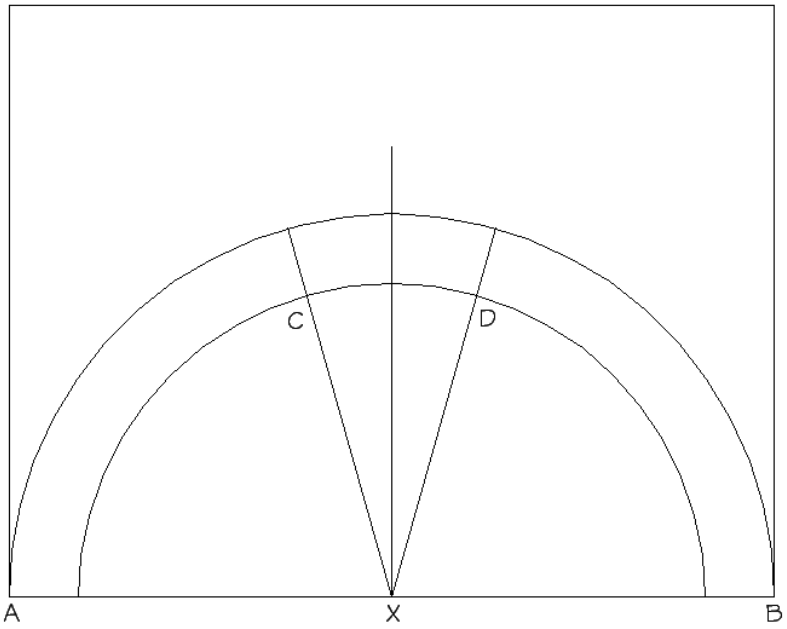

Figure 13.5

6. Now, you have merely to bisect the remaining angles AXC and BXD on each side into two, then 4 sections, and in so doing you will mark off the respective voussoirs of the entire arch (**Figure 13.6**). Square them off, as we have done to several, by merely converting the arcs of each, top and bottom, into chords. In our illustration, note the difference in size of the keystone to the voussoirs.

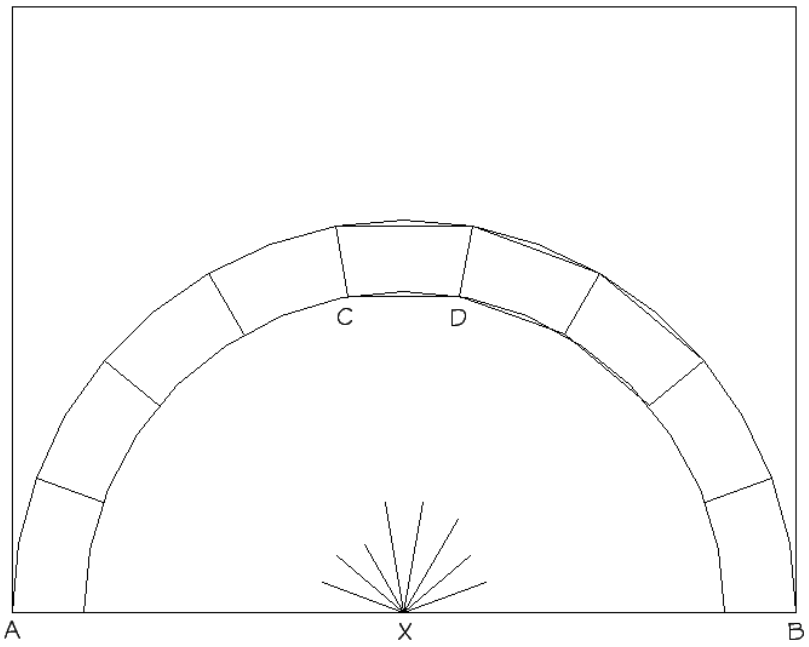

Figure 13.6

7. Yet another solution to designing an arch with an odd number of voussoirs is shown in **Figure 13.7**. Once again, you have but to bisect a half-circle into an even number of sections—in this case eight—but add one additional block under the base line as we have done (block A). By bisecting this block and carrying the line through center point x to the block opposite (block I), you will create a "new" base line, tilted though it is, which will now give you seven voussoirs, with two half-sized blocks at each end. A perpendicular to this new tilted base line will be seen to run through the keystone, now properly sited at the top—as long as you turn your design to a slight angle!

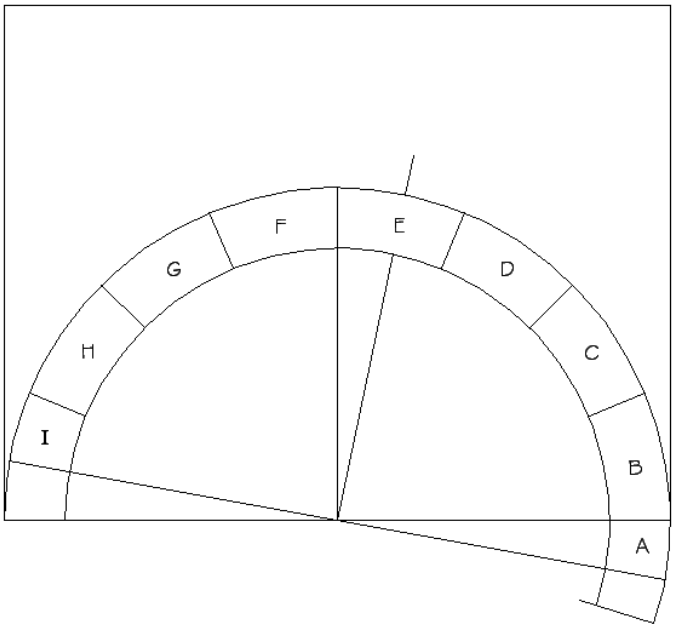

Figure 13.7

8. But you may not want such half-sized blocks supporting your arch. It will be an easy matter to enlarge them somewhat by drawing yet another line from the base corner of block I to block A, and adjusting their design somewhat with a flattened base, as we show in **Figure 13.8.** Because these two blocks will fit snugly up against the wall and are somewhat different in shape than all the other voussoirs, we can refer to them by their proper names, impost blocks. Such blocks are usually upright affairs at the "springing" of the arch, or where the arch kicks off from the supports at each end.

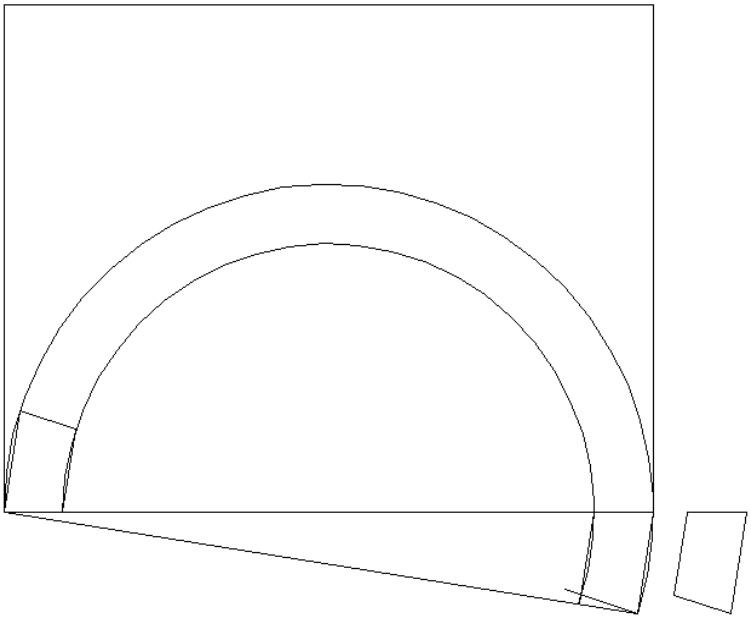

Figure 13.8

9. If you use this system, you should be aware that your finished arch will be slightly higher as the result of lengthening the impost blocks, so make sure your ceiling is high enough to accommodate it. Or, you can always reduce the height of the impost blocks by cutting off equal portions of the flat bases. (Alongside our Figure I've separated out a drawing of the impost block, free of any confusing "work" lines.) You will note too that your arch has a better, more professional look.

10. But now that we've examined the "easy" techniques, let's look at several of the more "official" methods, with more interesting results. Next, we will "find" and place the keystone by dividing the half-circle into a series of sub-units. In **Figure 13.9**, we've spun a half-circle on the base line at x, but note that on each side, we've gone somewhat below the base line. Construct perpendicular AX on center-point X of the half-circle; bisect one of these quarter sections into eighths, BX, and then bisect the eighth section closest to the perpendicular line into sixteenths, CX, and finally into 32nds, DX.

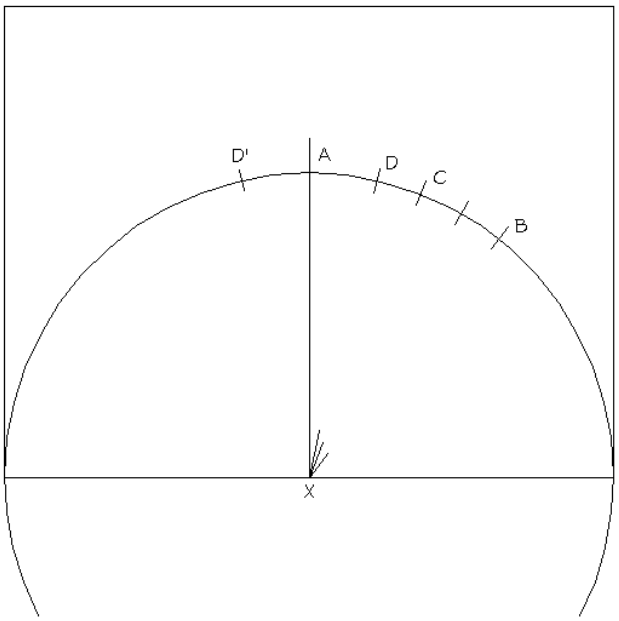

Figure 13.9

11. Now, set your compass to the distance of arc AD, with the point at A. Mark off the keystone by spinning a half-circle over to D' on the other side of the perpendicular. The keystone chord DD' can now become the official size of all the voussoirs, and so we can mark off these chords all the way down both sides of the arch, ignoring all other marks: DE, EF, FG, GH down the one side, and D'E', E'F', etc., down the other. You will note that the lowest arcs on each side cross over the base line, and we have used these to create two attractive impost blocks, which rest on a new base line, H'H. Be careful to be exact, so that all your voussoirs are identical! (**Figure 13.10**). Square off the inner and outer arcs with chords, and your arch design is ready for the next stage. Enlarge one of the Impost block panels and one of the voussoir panels to the scale you desire, and use these as we've instructed to make the desired number of units: two impost blocks,

and seven voussoirs. For a desk-top model, a net can be designed (as we've shown previously), and for a large-scale construction, cardboard pieces can be cut to size and taped together. Cut all of the cardboard pieces so that the corrugation follows the curvature of the arch, maximizing its strength.

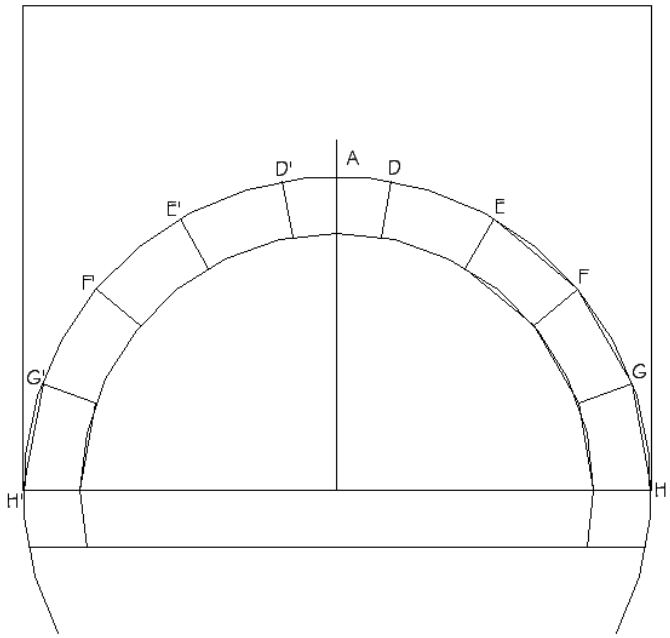

Figure 13.10

12. When enlarging the scale model measurement to the giant models, the slightest variations in measurements, no matter how careful you have been, can result in deviations which could affect the shape of your finished arch. Just before beginning assembly, lay the face pieces of the arch flat in the space you have chosen for it, just to assure that everything is going to "fit."

13. You may find that the arch is too tight for the space—or too loose—which at this point can be corrected by redesigning the keystone, widening or narrowing its dimension, or even correcting its angles. For this reason, the keystone should always be constructed last. That's what the Romans did, and that's what it is there for!

14. After assembly, other deviations may be corrected by slipping pieces of cardboard between voussoir sections where some spreading has occurred. That's what the cement in real arches often does! It is not a perfect, flawless system, but there are several ways of correcting such deviations. That's one of the reasons arches have stood for so long, and why they are so strong.

15. Lay out all the parts for one voussoir in a net, and do as much taping on the inside as possible. This will eliminate tension when the assembly is folded up. Reinforce all exterior edges of the block with long strips of wide cellophane or duct tape. Use small pieces of tape to hold any two edges together at the proper angle, then apply a longer strip

along one full edge, fold it over at the middle, and work the tape into place from the center out. Rub the tape down hard with your fingernail to make it adhere firmly.

16. As each block or voussoir is finished, set it along the wall, ready for assembly. Gather all of your helpers together (as well as any curious spectators). Put the impost blocks in place, and then have one volunteer stand by each impost block to put the first voussoir in place at each end. This first block may stay in place by itself--or it may not. In any event, two more volunteers can install the next two blocks on each side, and it will be necessary to hold them in place. The next set of two blocks can now be set in place, carefully aligned with those already installed. Soon, only one block will be left--the keystone. As this one goes into place, it may be necessary to adjust the other blocks somewhat in order to ease the keystone into place. Once secured or "locked" by the keystone, the bridge will become a solid structure, and all helpers can now abandon their positions. The bridge will stand by itself.

NOTE: if the large arch is to be in place for a long time, or if some of the connecting faces appear to be crushing or giving in under the weight of the arch, interior braces can be designed and installed in every block rather easily. On the wedge-shaped voussoirs, measure the lengths of the top and bottom of the block, and its diagonal on the inside (**Figure 13.11a and 13.11b**). Cut two flat wedge-shaped cardboard pieces to these dimensions, and cut a notch extending half-way through each. Hook the two pieces together in the form of an X. This assembly should fit comfortably inside the block, adding considerable reinforcement (**Figure 13.12**).

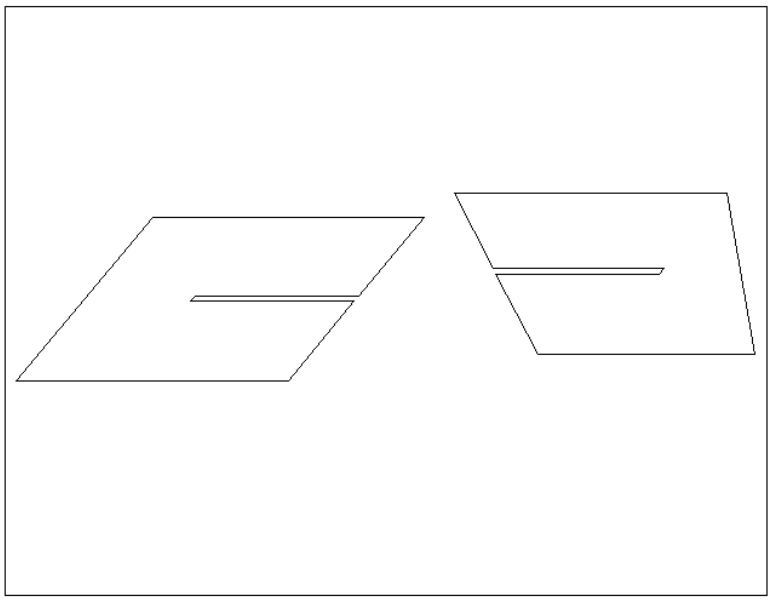

Figure 13.11a

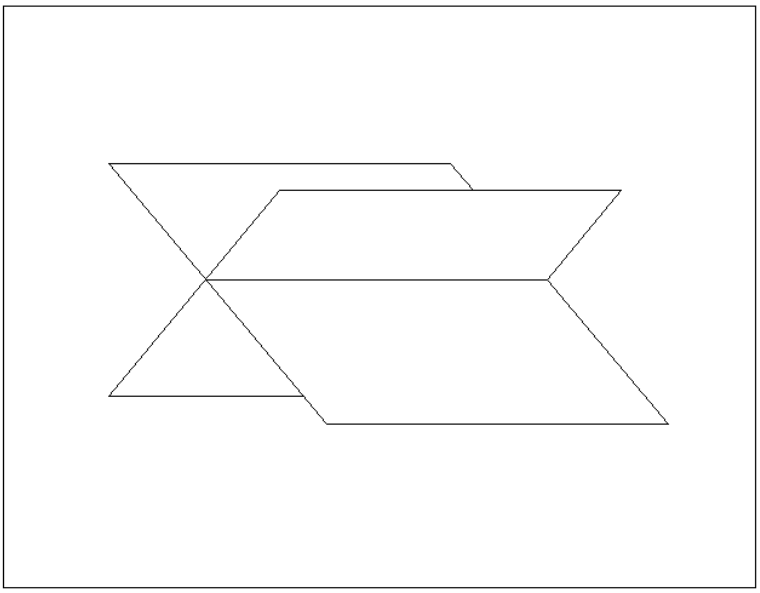

Figure 13.11b

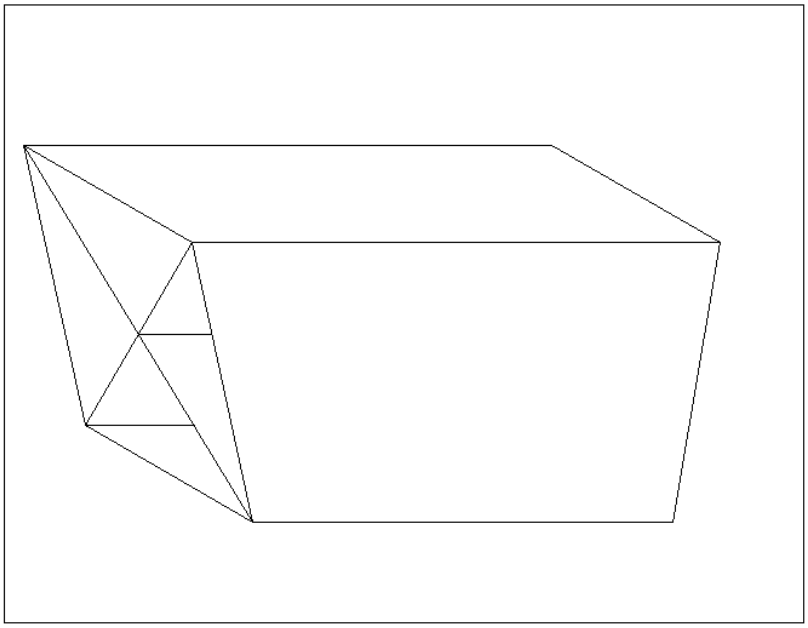

Figure 13.12

2. The Segmental-Arch

In instances where the span between the walls is quite long or the ceiling of a room is too low to build a semi-circular arch, a segmental-arched bridge can be designed and adapted to fit the space. This is not quite as easy to achieve as a semi-circular arch, which in any and every situation is a predictable half-circle, no matter what the size.

Steps:

1. With a segmental arch, the space dictates the design, but here is a formula that should work in every instance. Measure the distance between the two walls and the ceiling height in the area where you plan to install the finished bridge.

2. Translate these dimensions to a graph-paper rectangle using the scale of 1/4-inch = 6 inches. Your actual measurement may not quite fit this scale by a few inches either way, or the best thing to do for the moment is to round off the measurement to the lower number. For example, if the span is 22 feet 7-1/2 inches, translate this to the graph-paper scale as 22 feet, 6 inches. Later on, we will demonstrate a way to compensate for the "lost" 1-1/2 inch.

3. Having transferred the dimensions of your area to graph-paper (**Figure 13.13**), determine center-point X on base line AB, and construct perpendicular to X, carrying it well below the base line. In the case of a semi-circular arch, which is based on a true half-circle, its center point is found on the base line. But since a segmental arch is based only on a section of arc (less than a half-circle), its center will be located at some point along the perpendicular below the base line. **Note: Use Figure 13.13 to follow steps 4 through 7.**

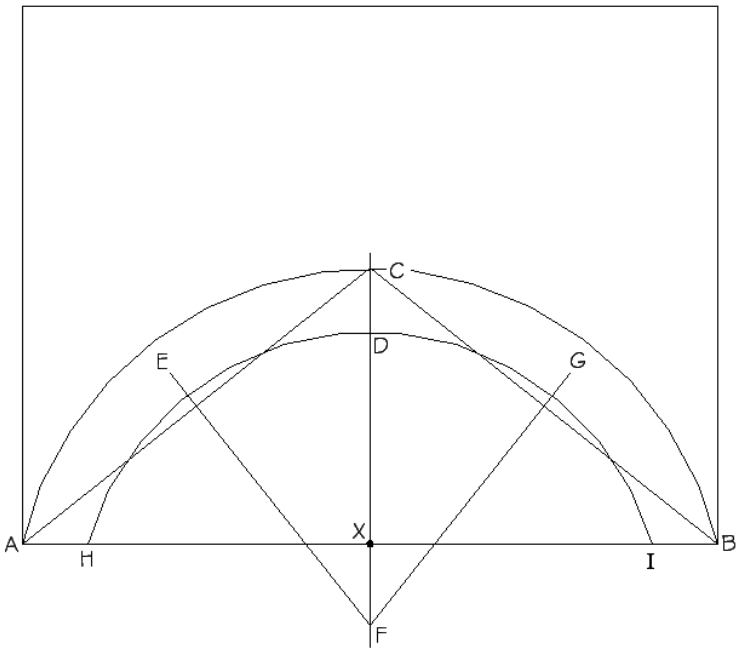

Figure 13.13

4. How do we find the appropriate "center" for our segmental arch? First, we must determine just how high our arch should be. If the ceiling in your particular case in quite low, a clearance of about six inches is desirable, so that in our drawing C on the perpendicular will become the highest point of our arch atop the keystone. Measuring down another inch (1-inch = 2 feet) to D will determine the bottom of the keystone. Of course, if the ceiling is too high to matter and the great length of the area is at issue, the question to be answered is how high any of the participants in the bridge-building activity

can reach in order to put all the “stones” in place without getting up on chairs, ladders, or lifts. If the crown of an arch is too high, setting it in place could become a dangerous proposition. I know! I’ve been there!

5. Our example is based on a 16-foot span with a 7 foot ceiling, and the placement of the keystone five feet overhead. The overall thickness of our arch is about 18 inches. (Arches with a longer span, say 25 to 35 feet, should be slightly thicker, about 30 inches, and should be braced internally.) On your graph-paper design, place your C and D measurements accordingly.

6. Draw lines from C to A and from C to B, which will become the two chords needed to find the center for our arc. Using C and A as reference points, construct perpendicular EF, and extend it until it reaches the perpendicular below the base line. Repeat this process with chord CB, creating perpendicular GF, which will also cross the base line to reach the perpendicular. This establishes the center of your arc. Place your compass point at X, and sweep an arc from corner A to corner B, which should cut across the perpendicular at C.

7. Next, with the compass point still at X, extend it to touch D on the perpendicular, and sweep another arc from point H on the one side to I on the other. This provides both the outer and inner aspect of your arch, which is now ready to be divided into voussoirs.

8. Such as it is, this arch isn’t very attractive or interesting. Furthermore, as the arch settles with time, its low, outward thrust would soon begin to crush the sharp end-tips which butt against the walls on both sides. And while the arch is high enough to walk under at its center, it is much too low along the sides. There is a simple solution for all these problems. By installing impost blocks in these areas, we could relieve that stress, and add considerable beauty, support, and height to our design. The impost blocks do not need to follow the same curvature of the arch, but may be two upright support piers on each side, with a slightly angled top to match the angle of the first voussoir which will rest upon it (**Figure 13.14a**).

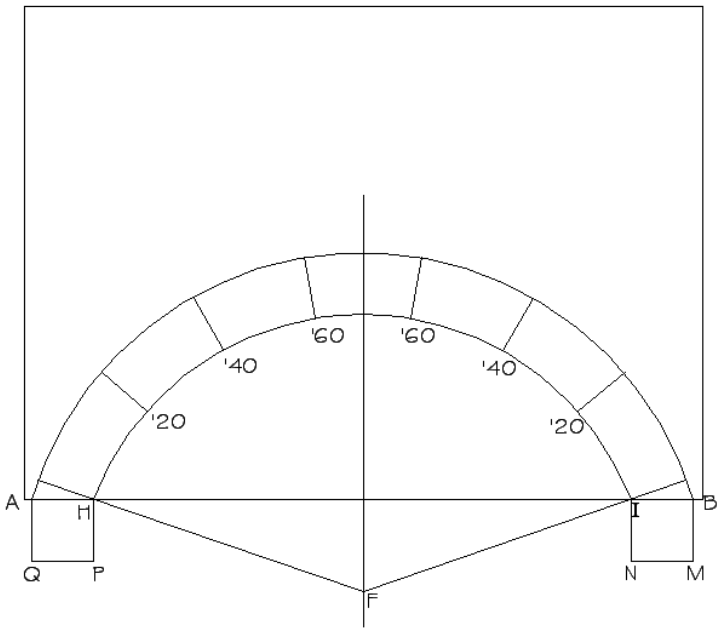

Figure 13.14a

9. Draw a line from center point F to H on the base line, and continue the line to the wall close to the one end of the outer arc. Another line from center-point F through I to the wall on the other side will result in two small triangles in these areas, which will become the tops of our two impost blocks. By extending the wall line downward somewhat below the base line (M), we can create an impost block of any practical height, as we have done in our figure. A parallel line of the same length from I to N will give us a full impost block, just as soon as we connect MN for the impost base. Do the same on the opposite impost, with extended lines AO and HP. But be careful not to make your impost blocks too high, or the crown of the arch may exceed the height of the room. A line drawn from O to M will give you the new floor of your room, so you can see the new shape of your arch.

10. Now, how can we determine the number and size of the voussoirs needed? The simplest process would be to resort to a protractor, set at F and lined up along line HF, which will determine the angle formed by HFI. Let's say the angle turns out to be 103 degrees. What odd number will most easily go into 103 degrees? Nine will go 12 times into that number very conveniently, but what do we do with the 4 degrees left over? Simple—we add these to the keystone. The keystone then takes 16 degrees of arc, 8 on each side of the perpendicular. Or, if the angle had been 95 degrees, we could still use nine voussoirs at 12 degrees of arc each, subtracting 4 degrees from the keystone. **Figure 13.14a**, as it turns out, has a 144 degree span, which allows us with the use of a protractor to install 7 voussoirs at 20 degrees each, with a keystone taking up the remainder at 24 degrees.

11. The number 144 is more perfectly divided by 9, which would produce all voussoirs and keystone of the very same arc: 16 degrees. Such a nine-unit arch is reproduced in **Figure 13.14b**. Chords drawn along the tops and bottoms of every

voussoir will square them off for easier cutting. Note in **Figure 13.14a** a "correction" on the right side to adjust the thickness of the voussoirs to match the size of the impost block, by sweeping out a new arc. This correction is further carried through in **Figure 13.14b**.

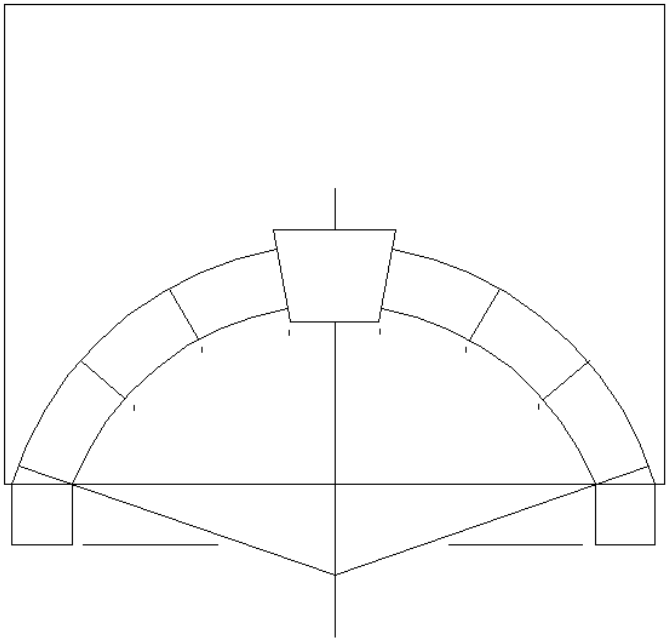

Figure 13.14b

12. As in all previous cases, one of these voussoirs and an impost block can be enlarged to become the template for the net (small model) or for all the cardboard pieces (large model) to complete a free-standing arch. The keystone, too, is an independent piece, that may be of a different size. Make this piece last, and adjust its size based on your final layout on the floor of the room where the arch is to be installed. In the last figure, we call your attention to a playful and deliberate enlargement of the keystone! There is more "function" than "fancy" in such a design, since an enlarge keystone can be adjusted up or down to make up slight deviations in the size of the arch. Still, when your giant cardboard arch is finished, the keystone literally cries out for decoration, such as the school logo, or some other design.

13. Remember the 1-1/2-inch discrepancy we set aside a while ago? If we neglect to add this slight deviation back into the design somewhere, the finished arch may fall some-thing short of fitting the space perfectly. The simple solution is to "adjust" the keystone by this dimension before cutting it out, and everything should fit perfectly.

14. Here again we repeat several reminders: cut all the cardboard pieces for the face sections to the proper size, so that the direction of the corrugation follows the curvature of the arch; this, as we have previously indicated, will add considerable strength to the finished bridge. When one complete set of face pieces has been cut out (those "flat" pieces which reproduce the drawing with no added depth), lay out the arch flat on its side between the two walls to see how it will "fit." Sometimes even the most careful designers

and builders make slight mistakes in measurements, and it is better to find out now than later, after construction is complete. Any slight errors can easily be corrected by altering the keystone by adding or cutting back.

Additional Exercise:

1. A somewhat more attractive bridge can be designed by using two different center points for the inner and outer arcs (**Figure 13.15**), which tends to thicken the bridge at each end, with a thinner span at the center. To accomplish this, follow all the steps given above, but before drawing in the inner arc, drop the compass point below center-point X along the perpendicular, and create the upper arc as you desire. But be warned: this means that you will be required to do a great deal more individualized piece work, since each set of two voussoirs (opposites) will be different from every other set. Such a design works most easily on arches of short span, but is more attractive on long-span arches, especially when the deck of the arch is almost flat.

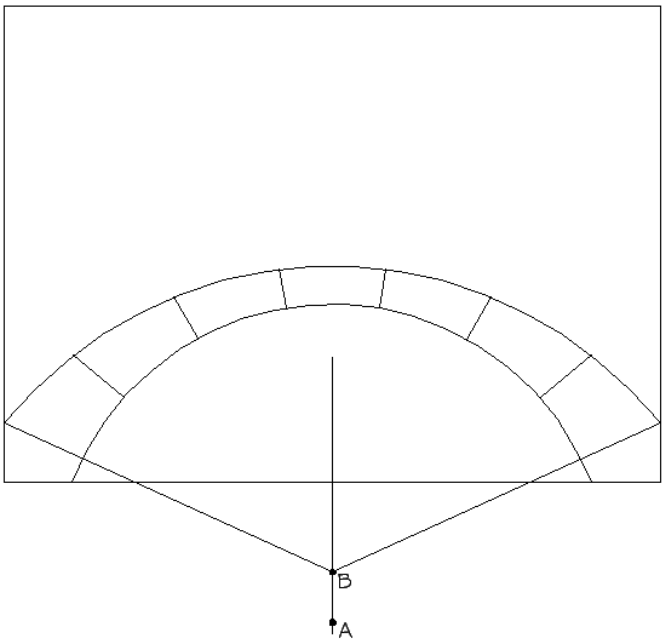

Figure 13.15

2. **Figure 13.16a** and **13.16b** are templates for the arch design shown in **Figure 13.10**. This differs from **Figure 13.1**, in which all 9 voussoirs are identical and there are no impost blocks; this version has impost blocks and 7 voussoirs. **Figure 13.16a** is pattern for the impost block, two of which are necessary for the model. **Figure 13.16b** is the voussoir pattern, and you will need to make seven of these. You can enlarge these patterns on a copy machine, or with the use of compass and ruler, transfer them to poster-board or even to large sheets of corrugated board to make a simple arch of most any size. As we said earlier, you will want to brace both ends of the arch, so that it will not splay out. Filling the impost blocks with sand or marbles will do the trick.

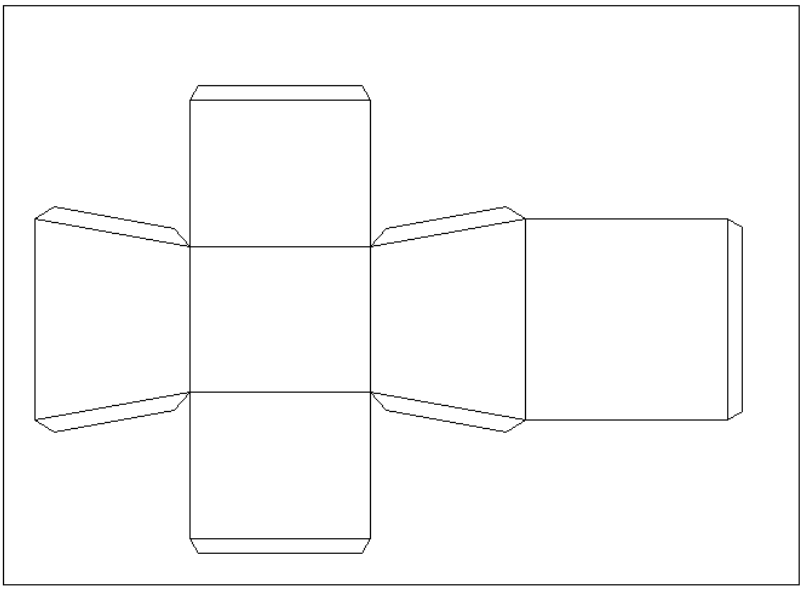

Figure 13.16a

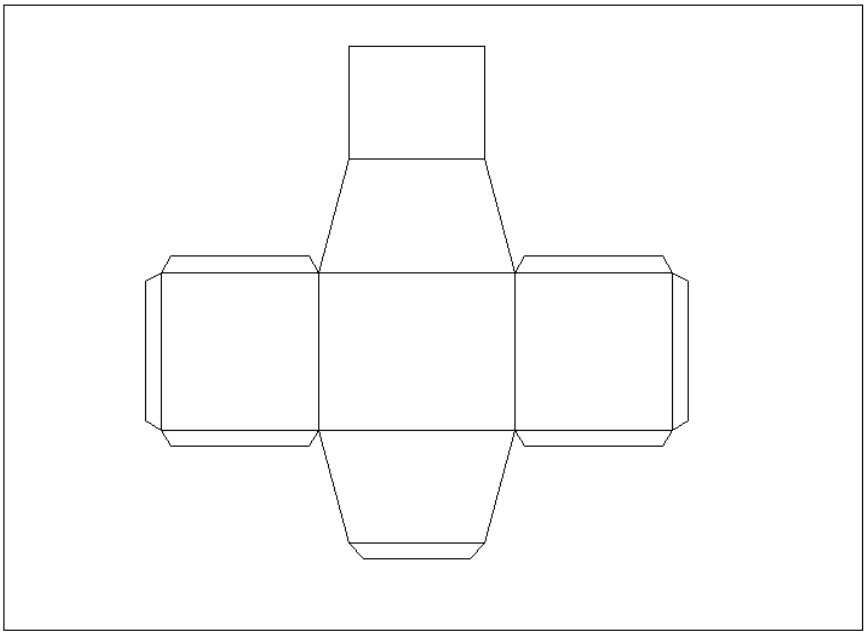

Figure 13.16b