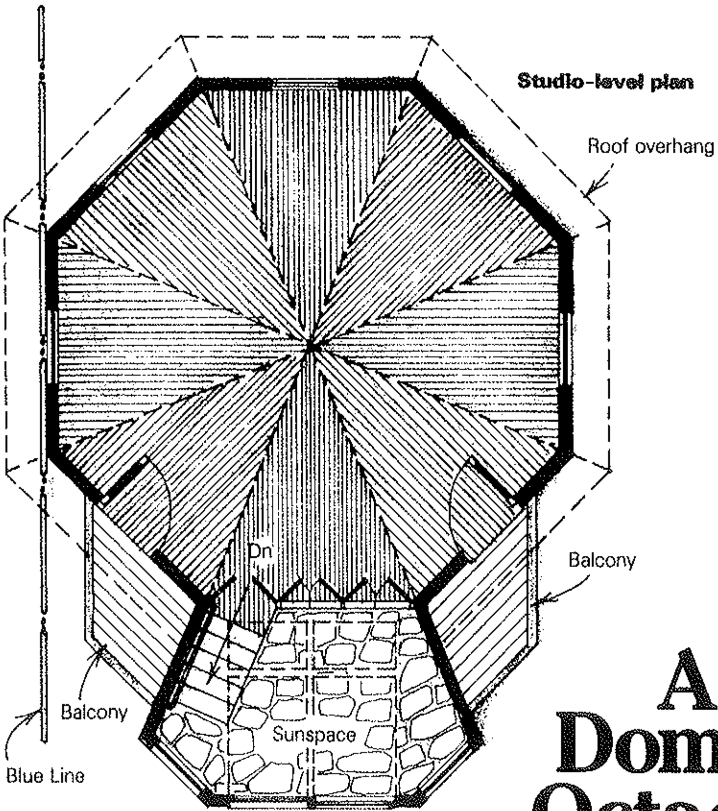
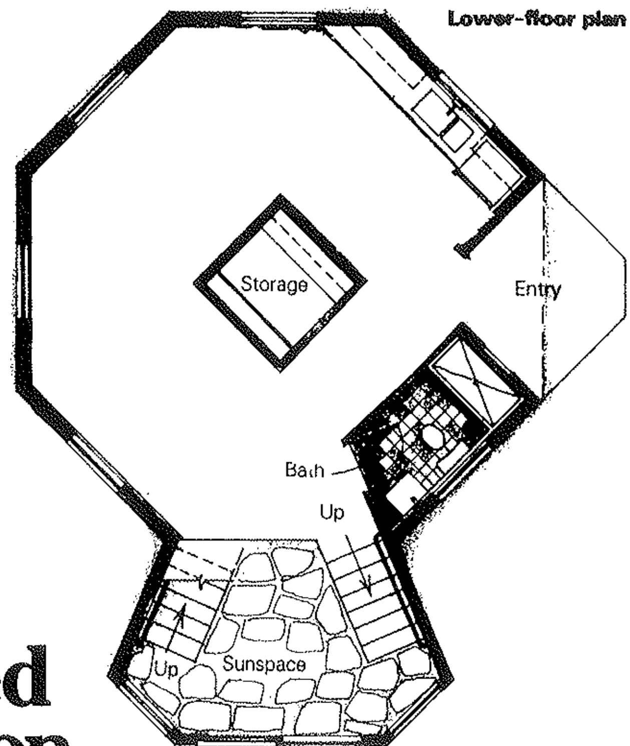
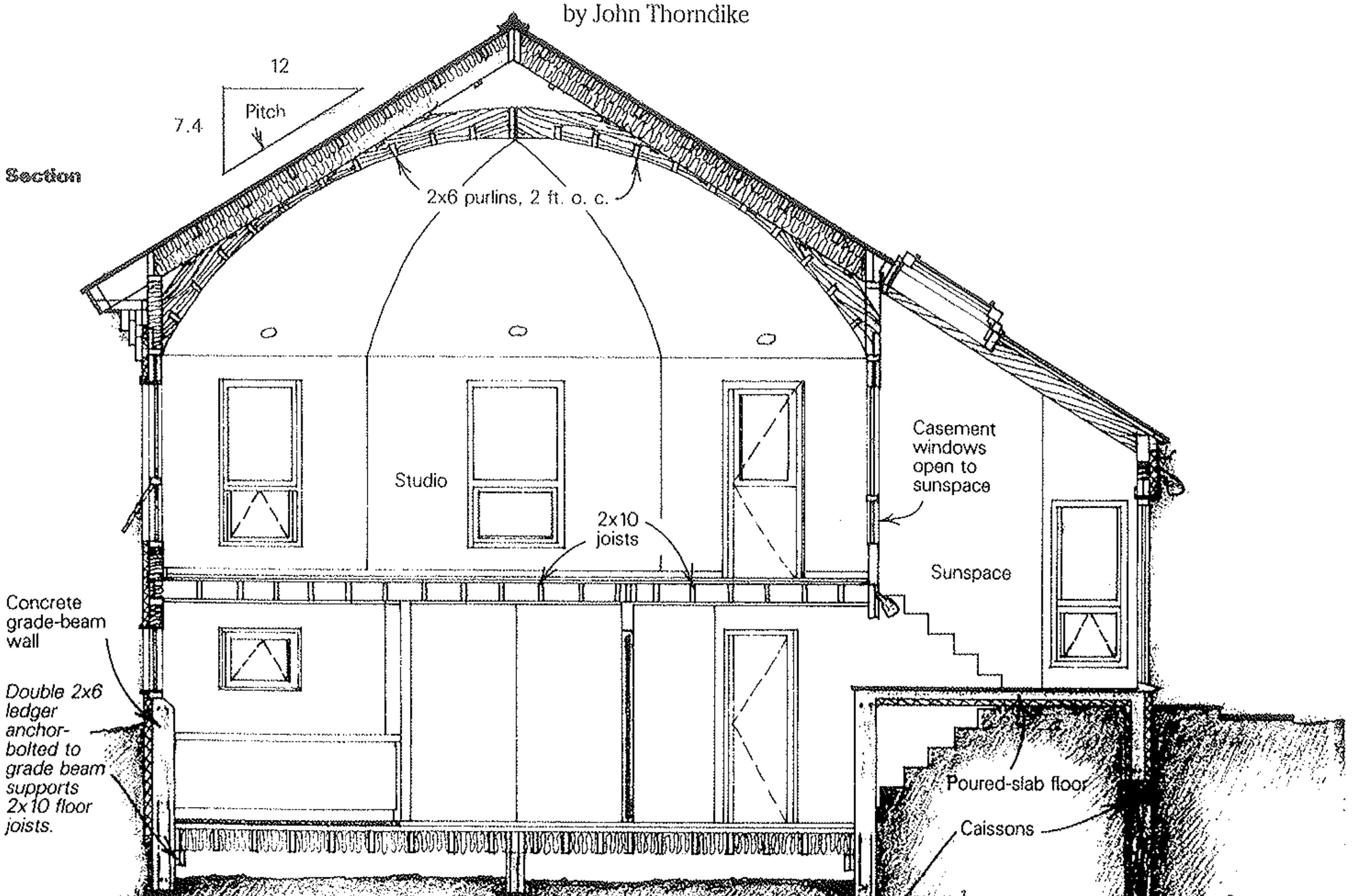



# A Domed Octagon

## Tricky carpentry in the curved ceiling beneath an eight-sided roof

by John Thorndike



The western edge of Boulder, Colo., is marked by a "Blue Line" that limits the extent of city services and utilities, thereby discouraging the creep of housing. Beyond this statutory line the stark, buff-colored foothills of the Rockies rise sharply from the high plains. Nancy Stetson, an artist who has lived in Boulder off and on since 1957, bought one of the few remaining lots along the western Blue Line in 1984. Because a city irrigation ditch bisects the 50-ft. wide lot and local code calls for 5-ft. setbacks on either edge of the property, the size of Stetson's home and studio was restricted to a maximum of 25 ft. by 40 ft. Stetson explains that an old friend, Roger Burrows, had the idea for an octagonal structure and suggested the geometric proportions of the studio space, the creative heart of the house. The actual design and drawings were done by Phillip Tabb, a Boulder architect who specializes in solar and traditional designs. Working within the 25-ft. by 40-ft. limit and following Burrows' guidelines, Tabb designed a two-story octagonal structure with an appended south-facing sunroom. The ground floor of the building provides simple accommodations, and the second floor gives Stetson a large open space for her artwork.

The downstairs cooking, dining, sleeping and bathing areas in the Stetson house are all small. They surround a central storage area and occupy, all told, less than 500 sq. ft. Stairs lead up to the small five-sided sunroom, and continue up to the top-floor studio (drawings, facing page). This large octagonal room has extensive views of Boulder, the plains and the Rocky Mountains, and is capped by a lofty domed ceiling.

**The golden section**—The dimensions of the Stetson house—including the width of the octagon, the height of the walls and the radius of the second-floor dome—are all based on the golden section, a ratio that has been influential in both art and architecture since the time of the ancient Greeks. In a geometric figure, the golden section is a proportion in which the smaller part of the figure stands in the same relation to the larger part as the larger part stands to the whole. In the golden rectangle, the short side is to the long side as the long side is to the sum of the two. This proportion, denoted as $\Phi$ *(phi* in the Greek alphabet), is an irrational number (one that cannot be expressed as an exact integer or fraction) that approximates 1.618.

The Greeks often used the golden rectangle in the design of their buildings, and to this day artists, architects and designers regard the proportion as singularly harmonious. Modern times have brought extensive, if more pedestrian, use of the golden rectangle. The common 3x5 index card is an example, for 5 divided by 3 (1.666) is almost the same as 8 divided by 5 (1.60). The credit card (usually 2⅛ in. by 3⅜ in.) is also a golden rectangle.

In Tabb's design for the Stetson house, the total height of the first and second-floor walls

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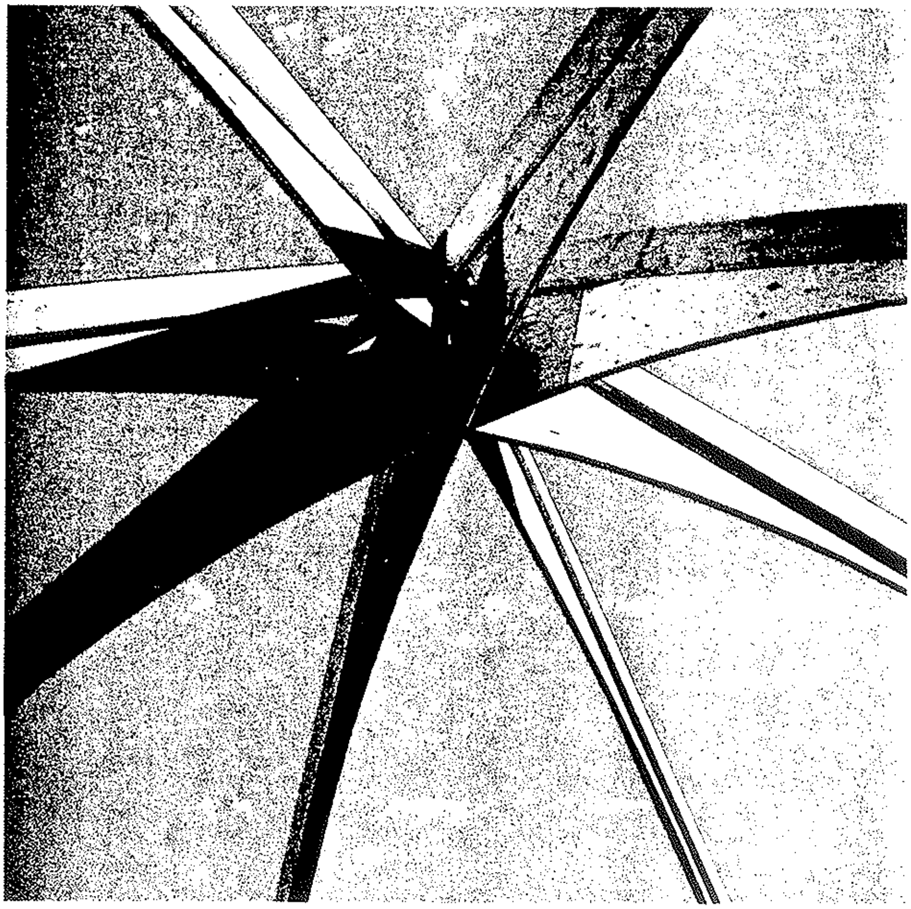
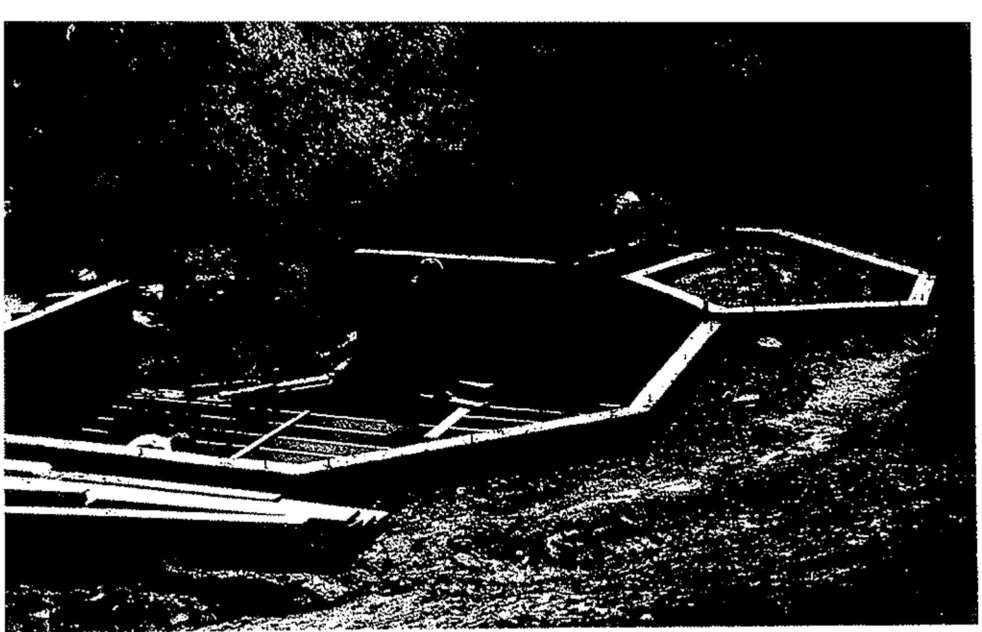
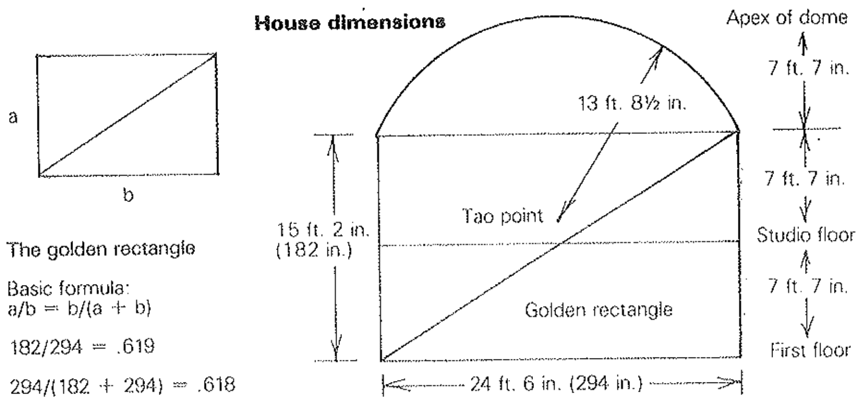


**Beneath the octagonal roof of this small house on the outskirts of Boulder, Colo., there's an open studio with a domed ceiling. The joinery at the roof peak, above, was a feat of geometry that challenged both architect and builder. Kitchen, bedroom and bath are on the ground floor; the house also includes a small sunroom (drawings, facing page).**

Drawings: Frances Ashforth



**Poor soil conditions at the site dictated an engineered foundation. The octagonal wall is actually a poured-concrete grade beam supported by concrete caissons. The small polygon on the right is the foundation for the sunspace entry.**



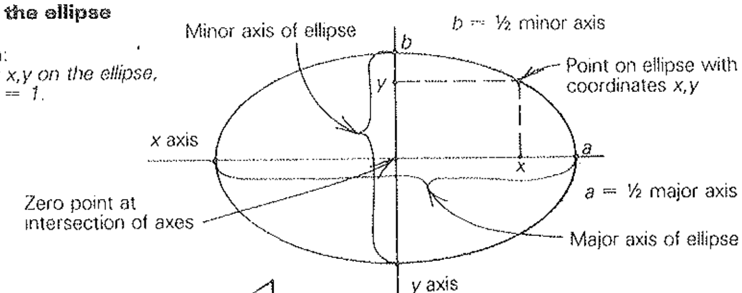

Basic formula:
$a/b = b/(a + b)$

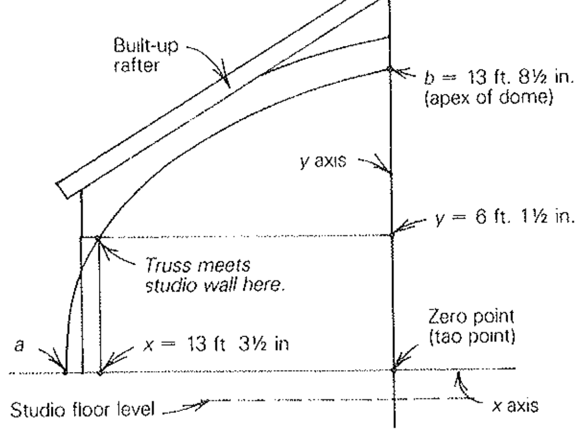
$182/294 = .619$

$294/(182 + 294) = .618$

**Solving for the ellipse**

Basic formula:
*For any point x,y on the ellipse,* $x^2/a^2 + y^2/b^2 = 1$.




Solving for a

Basic formula:
$x^2/a^2 + y^2/b^2 = 1$

Plug in known values for $x$, $y$, $b$ (convert ft. to in.):
$(159.5)^2/a^2 + (73.5)^2/(164.5)^2 = 1$

$a = 14$ ft. $10\frac{1}{4}$ in.

(15 ft. 2 in.) is the short side of a golden rectangle whose longer dimension is the distance across the octagon (top drawing, left). This rectangle is capped by an arc that determines the form and dimensions of the dome's ceiling. The arc's radius of 13 ft. 8½ in. is measured straight down from the peak of the ceiling to a spot 17½ in. above the studio floor—the theoretical focal point of this creative space. If you sit on the floor at the center of the studio, this focal point or *tao*, in Tabb's words, will be located somewhere in the middle of your chest. The roof pitch, which is 7.4-in-12, is the diagonal of a golden rectangle.

**Caissons and formed walls**—Barry Campbell, a long-time Colorado builder, supervised the construction of the Stetson house from the initial survey to the installation of the copper roof. Even before construction started, Campbell knew that the house would be tricky. The original plan to build on a poured-concrete slab had to be scrapped after a soil test showed that much of the subsoil consisted of expansive clay shale. Instead of footings, holes were drilled for poured concrete caissons. The drilling was done with a 12-in. auger in the presence of a soils engineer, who determined the depth of each hole. The shallowest hole turned out to be 14 ft. deep; the deepest was 24 ft.

The unlined caissons were drilled and poured the same day. Instead of using cylindrical forms to bring the tops of the caissons above ground, the concrete was capped off 3 ft. to 5 ft. below existing grade. This was done to avoid the overflow and mushrooming of concrete that is often a problem when tubes are used. An expansive soil pushing against the mushroomed portion of a caisson is quite capable of cracking the caisson in half. Right after the caissons were poured, four high-tensile lengths of steel rebar were driven down into each caisson. To guarantee the proper bond between caissons and the subsequent grade beams, the rebar was allowed to project 4 ft. beyond the top of each pour. A few days after the pour, a careful backhoe operator excavated the site to the top of the caissons.

To lay out the octagonal formwork for the poured concrete grade beams that would support the walls of the structure, Campbell shot the site with his transit. The surveyors gave him two points on the Blue Line, marking the westernmost corners of the octagon. Setting the transit over one of these points and sighting the other point, he rotated the transit 135°, the interior angle of a regular octagon, and established the first of the two northernmost corners. Then he set the transit over that corner, rotated another 135°, and so continued around the octagon until a final shot back to the Blue Line provided a check on accuracy. Measurements at this point had to be exact if the roof construction was to go smoothly later.

Campbell next formed and poured the 8-in. wide concrete grade beams for the ground-floor walls. The grade-beam foundation (see *FHB* #16, pp. 31-37) is continuous, and reinforced with paired runs of #5 rebar positioned near the top and bottom of the beam. Campbell used cardboard void boxes to keep the grade beam off the ground between caissons, thus isolating the beam from earth movement. As he had for the caisson pour, Campbell hired a concrete pump truck to ease what would otherwise have been a troublesome hillside pour.

"Difficult pours are time-consuming," Campbell says, "so even with the use of a vibrator you tend to get dry joints and honeycombing. A pump truck gives you a smoother, faster, more uniform pour. In this case I think the grade beams wound up a lot stronger." Campbell suspended a joisted floor from the grade beams (photo facing page), using a double 2x6 ledger that was anchor-bolted to the beams.

Tied to the top edge of the grade beam with anchor bolts, a short kneewall of 2x8s, 16 in. o. c. brought the walls of the octagon to the 2x10 second-floor joisting spaced 16 in. on center. Second-floor walls are standard 2x4 construction. In addition to R-13 batt insulation between studs, rigid 2-in. T&G polystyrene insulation was fastened to the plywood exterior sheathing with ConTech PL 200 construction adhesive (Rexnord Chemical Products, 7711 Computer Ave., Minneapolis, Minn. 55435) and with 16d nails driven through plastic gaskets. Because stucco was to be applied directly over the insulation, the nails had to be galvanized.

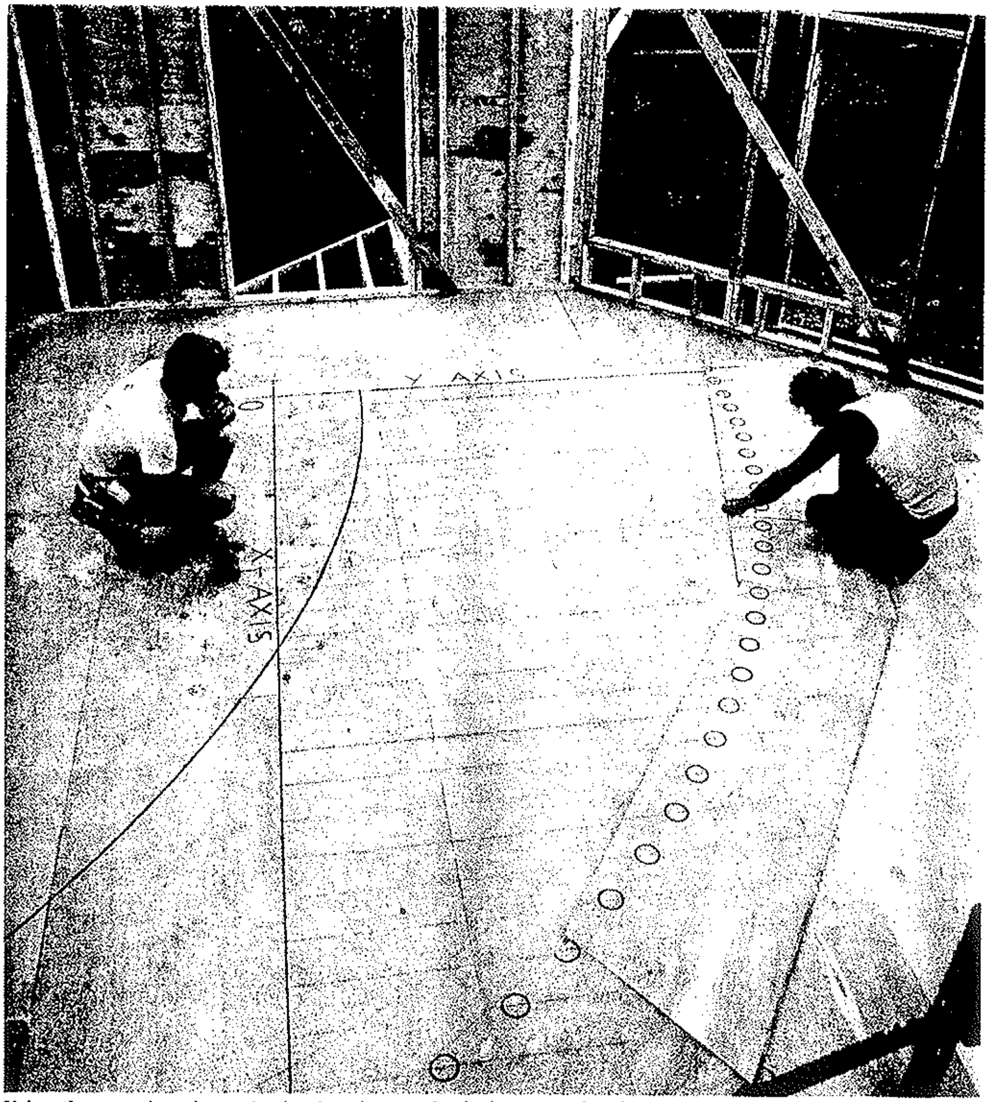
**Roof design and construction**—This is where the true thrills began. An eight-sided roof is the logical top for an octagonal house. But the studio's interior ceiling was to be domed, with the apex directly below the roof peak.

Tabb, his assistant Frank Richardson and Campbell collaborated on a design for site-built rafter assemblies that are straight on their top edges and curved along their bottom edges. The straight portion of each assembly consists of twin 2x12s. Sandwiched between these members are two layers of ¾-in. exterior plywood—the curved part of the rafter.

The curve of the domed ceiling is circular from the apex to the midpoint of any wall's top plate. But as the curve moves toward the corners of the wall, it becomes elliptical. Tracing the elliptical curve onto the plywood of each built-up rafter required a little math. The mathematical formula that defines the curve of an ellipse is: $x^2/a^2 + y^2/b^2 = 1$, where $a$ is half the major axis of the ellipse; $b$ is half the minor axis; and $x$ and $y$ are coordinates on the ellipse (drawings and equations, facing page). For any given point $x,y$ on the ellipse, $x$ will be the distance away from the minor axis and $y$ will be the distance away from the major axis. In the formula, $a$ and $b$ remain constant.

What we are after is $y$, for a series of $y$ measurements will give us the approximate curve of the ellipse. However, to find $y$, we first have to calculate $a$. We do this by using the same mathematical formula at a point where we know the $x$ and $y$ coordinates—the top inner edge of the studio wall, where the curved truss will rest. In this first calculation, $b$ = 13 ft. 8½ in.; $x$ = 13 ft. 3½ in.; and $y$ = 6 ft. 1½ in. All measurements have to be converted to inches. Solving for $a$, we get 14 ft. 10¼ in.

Once the two constants ($a$ and $b$) are known, the formula can be used repeatedly to find $y$ for a given $x$. Campbell used an $x$ interval of 6 in. ($x$ = 6 in., $x$ = 12 in., $x$ = 18 in., and so on), solving for y to find out the exact height of the rafter assembly at each distance away from the center of the studio floor. As an example, take the third calculation, made to pinpoint the height of the ellipse at a point 18 in. away from the central axis of the room. $x^2/a^2 + y^2/b^2 = 1$ translates to $18^2/178.266^2 + y^2/164.5^2 = 1$. So $y = 163.66$ in.




**Using the equation shown in the drawing on the facing page, head carpenter Barry Campbell (at right) and a helper plot the ceiling's curve at full scale on butted sections of ¾-in. plywood. Two layers of ¾-in. plywood will be sandwiched between a pair of 2x12s to form each built-up rafter. Cut in an elliptical curve, the plywood defines the shape of the studio ceiling.**

When he had all the figures, Campbell drew full-scale $x$ and $y$ axes on the studio subfloor and snapped lines every 6 in. parallel to the $y$ axis. Then 2x8 sheets of ¾-in. plywood were cut and butted together so that they aligned parallel to the approximate path of the curve (photo above). This allowed Campbell to plot the elliptical cutting line on the plywood.

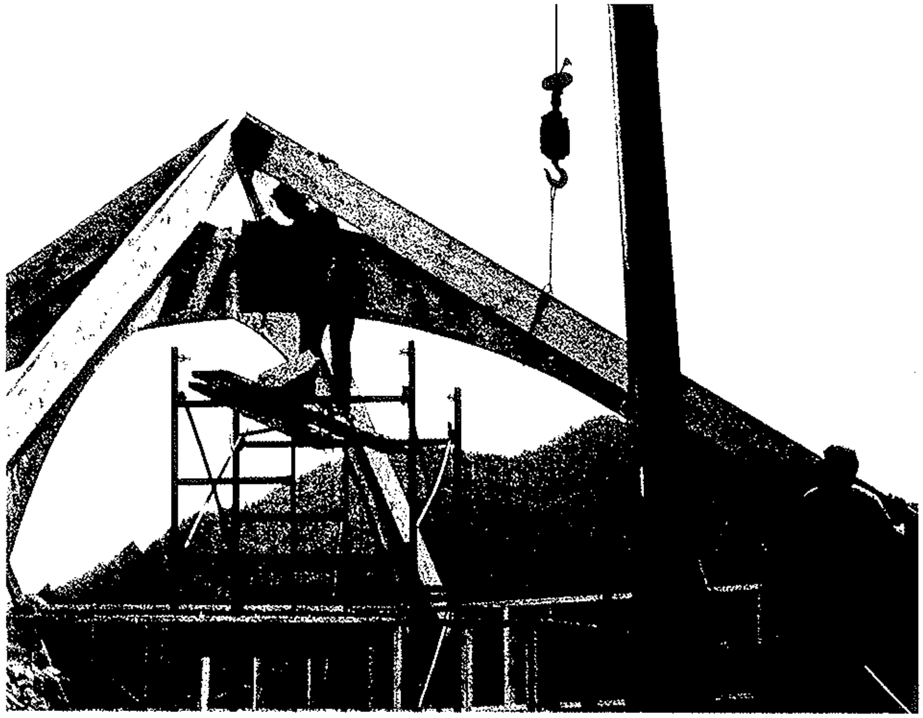
Once all the curved members were cut, they were laminated into pairs, using construction-grade panel adhesive and 1½-in. TECO nails, the same nails that are used to fasten joist hangers. The butted end joints in these curved pieces were staggered. Two-by-twelve rafters were then nailed to both faces of the plywood, completing the roof's eight rafters. The bottom curved section had to be cut to 3½-in. width to fit atop the double 2x4 top plate of the second-floor wall.

The rafter assemblies weighed less than 200 lb. apiece, but they were so unwieldy that Campbell called in a boom truck to lower them into place (top photo, next page). As shown in the top photo on p. 57, the joinery at the roof peak is complex but symmetrical. Each truss has its opposite, with the result a star-shape. The first four rafters to be erected form a cross of butt-joined 2x12s that was reinforced with a pair of custom-made steel gussets. Just below this peak, four vertical plywood edges join in an identical cross. The remaining trusses bisect the cross, and had to be bevel-cut 45° along each meeting edge.

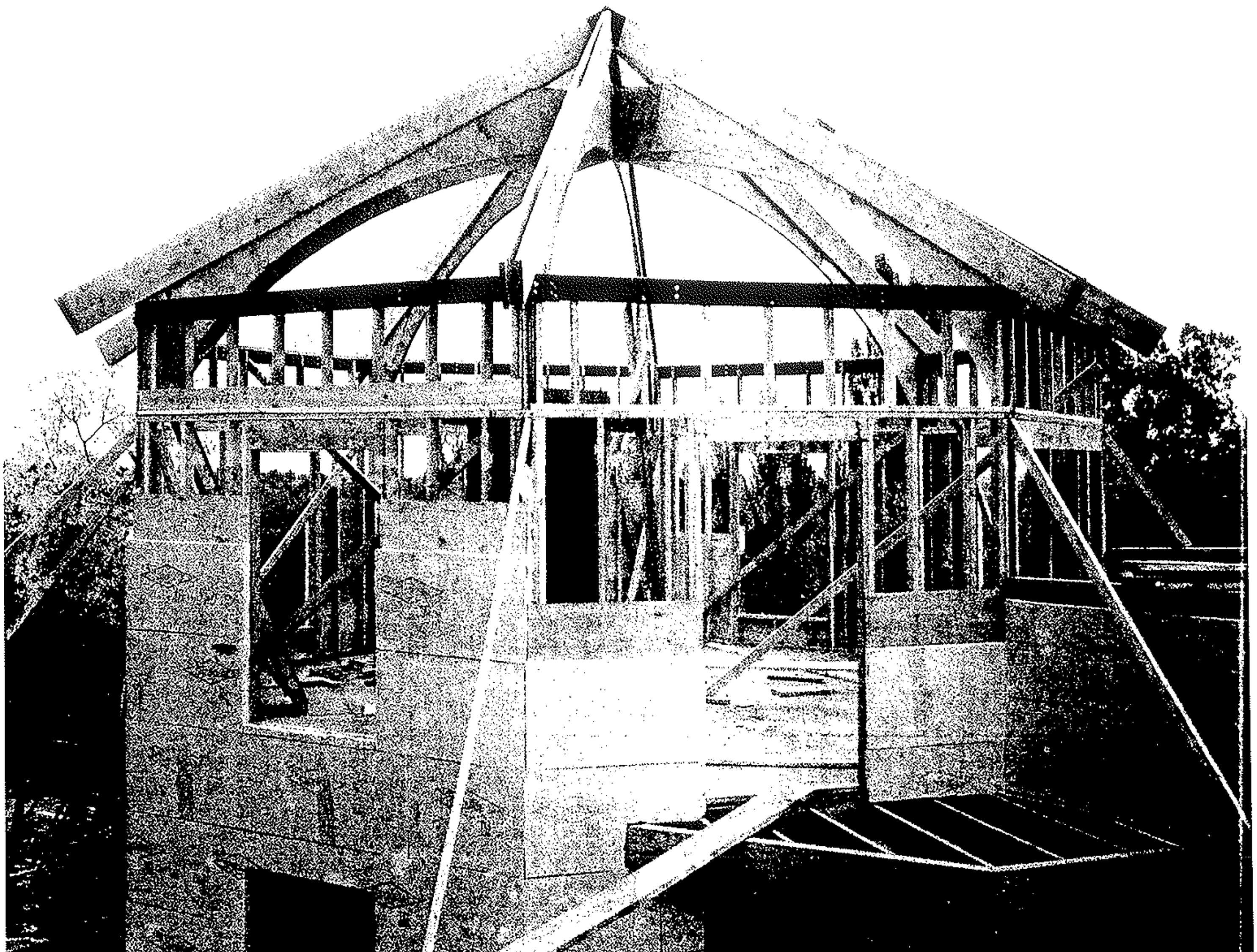
To provide much-needed lateral support between rafter assemblies, Campbell and his crew built a 2x4 kneewall along the top plate between each corner, where the rafters bear. To counteract the outward thrust of the roof, a steel tension ring was bolted along the outside edge of the kneewall's top plate (photo below). The tension ring was fabricated on site from ⅛-in. by 6-in. wide steel strapping and custom-made steel corner angles.

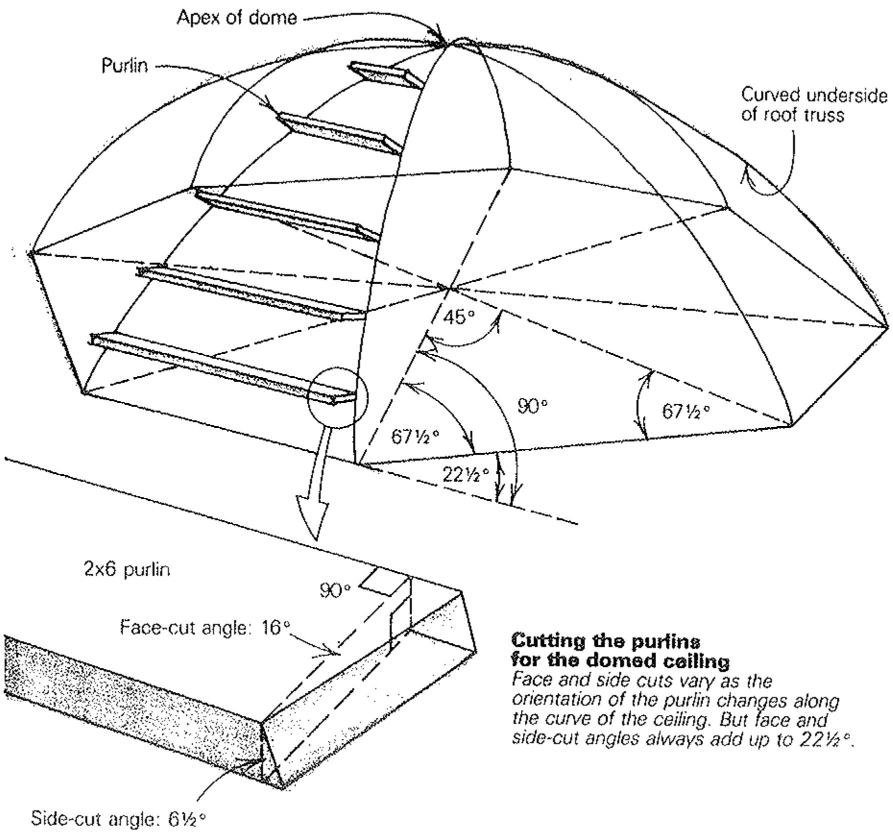
With the principal structural members in place, the crew set about closing in. Between each truss, two sets of 2x6 purlins were nailed and clipped in place with joist hangers. Both sets of purlins are concentric to the peak and spaced on 16-in. centers (bottom photo, facing page). The upper set of purlins was installed flush with the top of the 2x12s to provide nailing edges for the roof sheathing. Below these, a second set of purlins was nailed up, their bottom edges flush with the curving plywood edges of the trusses.

The face cuts and side cuts for the purlins had to be carefully calculated, and called for some test-fitting and trimming. But fortunately, all eight purlins are identical in each concentric course, so when one was made to fit snugly, it could be used as a pattern. Campbell discovered that the face cuts and side cuts for any purlin always add up to 22½°. All upper purlins have side cuts that are 14½° and face cuts that are 8°. The lower purlins were more difficult to cut because of the curved plywood that de-



**With the aid of a boom truck, above, workers maneuver a built-up rafter into position. At the roof peak, 2x12s were bolted to a custom-made steel bracket. Just below the peak, the plywood joins in an identical star. After all the rafters were installed (below), a tension ring made from steel plate was bolted in place along the top edge of the wall.**






**Cutting the purlins for the domed ceiling**
*Face and side cuts vary as the orientation of the purlin changes along the curve of the ceiling. But face and side-cut angles always add up to 22½°.*

**The roof received its final framing in the form of 2x6 purlins, which were installed with joist hangers and spaced on 16-in. centers concentric with the roof peak. The upper purlins are flush with the top edges of the 2x12s; lower purlins follow the curve of the domed ceiling (drawing, above).**

**To finish the domed ceiling, wedge-shaped pieces of rock lath were fastened to the lower purlins, and all joints were covered with expanded metal lath. Then a three-coat plaster finish was applied.**

scribes the domed ceiling. As shown in the drawing at left, face and side cuts vary, depending on the purlin's position along the curve of the ceiling.

Once complete, this secondary structural framing stiffened the roof significantly. It also created a sculpture of framing geometry for everyone to admire briefly before insulation and sheathing were installed.

The roof trusses hold R-38 of batt insulation. The top 6-in. layer is unfaced fiberglass, installed between purlins. Beneath this, 6-in. kraft-faced batts were installed with the paper surface facing down. One-by-two wood strips nailed to the bottom edges of the 2x12s hold this layer of insulation in place.

Subcontractors nailed rock lath to the interior ceiling purlins and added expanded metal lath at all seams. Then they applied three coats of plaster (photo above). A sheet-metal expansion joint with a U-shaped cross section was installed between the ceiling and the plastered walls at the recommendation of the plaster contractor. It allows the plaster to expand and contract without cracking on the walls or the ceiling.

The finished studio presents an interior surface that is as smooth and flush as possible. A minimal baseboard of 1x3 pine borders the oak strip flooring. Apart from light switches, the only hardware to project into the room are the four small sprinkler heads required by the Boulder Fire Department, and much lamented by Stetson, who wanted an entirely smooth interior.

The owner envisions the room as something more than an artist's studio. "I want to paint here, but also to work with music and other healing activities. The only furniture will be a few pillows on the floor, and the room will be kept like a stage. There's a fear in our society of empty spaces, but I think when the studio isn't in use, it should be empty. I'll move things in and out. This is a special room. I want to see what its effect will actually be." □

plan

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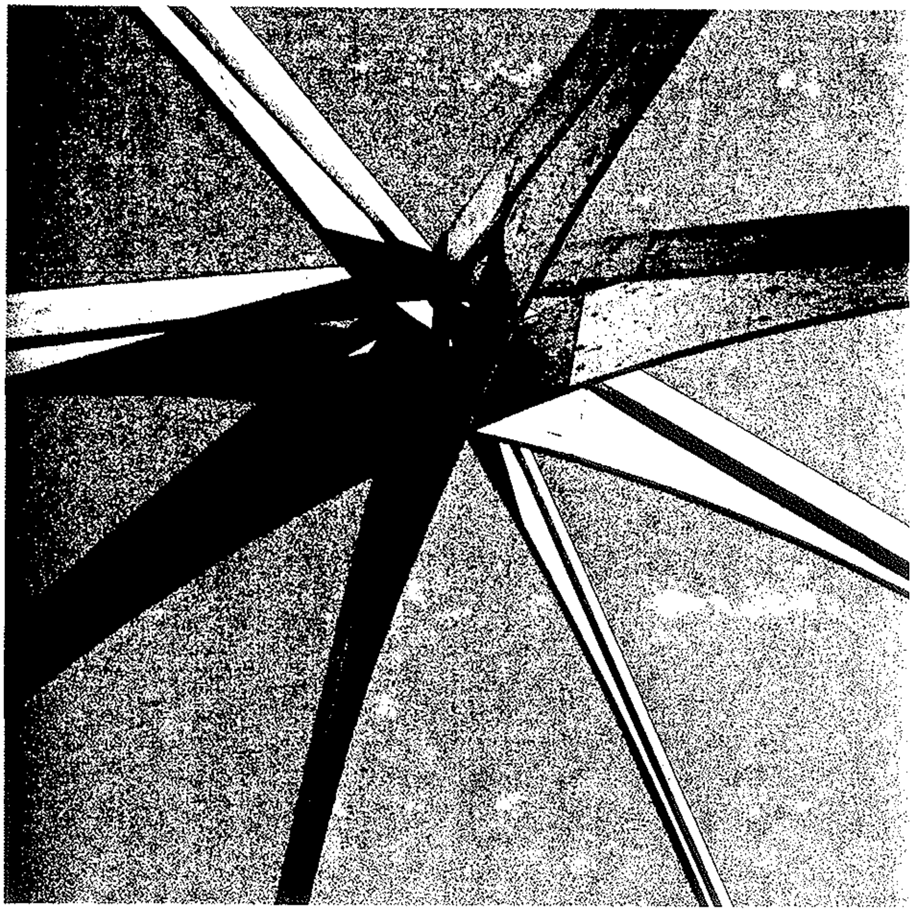

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