Triaxial weaves are characterized by three directions of yarn interacting at 60 degrees (Fig.1). In a previous article I described twenty-three triaxial weaves and outlined the mechanics of looms that manipulate diagonally traversing yarn sets. [24] All but one of these looms treats the two diagonal elements as the warp, as shown in Fig. 1A. This approach to triaxial weaves requires sophisticated mechanical means of manipulating the warp [22], which has been achieved elegantly in the Barber-Columbia TW 2000 loom. [27] Its traversing-warp design is undoubtedly the best design for weaving fine fabrics, especially since the weft can be inserted rapidly with a conventional raper shuttle. But there is currently no handloom available that meets the requirements of the traversing-warp approach. It is possible, however, to conceive of triaxial weaves with a conventional -- and conventionally manipulated -- warp and a diagonally traversing weft, as shown in Fig. 1B. The behavior of the traversing weft so closely resembles the movement of yarn in traditional flat braids that it is not difficult to adapt braiding techniques to explore triaxial weaves on an unmodified handloom.

1. Flat Braids.

The simplest braid, the three-strand braid shown in Fig. 2A, we all know as the basic pigtails. In another simple braid, the four-strand braid in Fig. 2B, two pairs of ends braid through one another. Fig. 2C shows a third pair -- a warp -- added to the four-strand braid. Though modified, the interaction of the original pairs is essentially the same. They braid through one another in an over-and-under plain or tabby weave. These crossing pairs occur in several triaxial weaves.

Even in the elementary braids of Fig. 2, the diagonal movement is clear. As each end reaches a selvedge, it reverses direction, as does the warp in Fig. 1A and the weft in Fig. 1B. The diagonally traversing elements actually constitute not two sets of yarn but a single, rotating set. The reversing/rotating diagonal elements dominate the design of any triaxially woven work.

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While the industrial triaxial loom could be the basis for a fine handloom for weaving triaxial fabrics with diagonally traversing warp elements, industrial braiding has little to offer to handweavers interested in triaxial weaves. Interestingly, though, industrial braiding machines have had the capacity to weave at least one triaxial variation since the nineteenth century. (26, 19) More recently, researchers have explored machine braiding as an approach to industrial triaxial weaving. (25) An examination of hand-braided flat braids does, however, provide useful insights for manipulating a diagonally traversing weft by hand.

Fig. 3 shows the diagonal braid or Peruvian belt braid.* Moving from right to left from the top, the yarn reverses direction at the left selvedge and travels back to the right in pairs, hidden from view. The braid begins at one contact point at the top and braids down, away from that point, until the full width of the braid is reached and the yarn reverses direction. Since only one direction of movement is visible, the diagonal braid highlights the rotation of the yarn. Fig. 4 shows the hidden structure.

Two flat braids closely related to one another are the edge-to-center French sennit and the center-to-edge Osage or chevron braid, Figs. 5A and 5B. The edge-to-center begins at two contact points and braids down, away from the rod, until the yarn from each edge reaches the center. Here each end reverses its role from the partially obscured 'inside' yarn to the dominant 'outside' yarn. Fig. 5B conforms to traditional spacing. At the selvedges, each end folds up over the next descending end and reverses direction. Reversal of roles in the center of the center-to-edge braid is opposite, from 'outside', to 'inside'. And at the selvedges, each end folds down under the next end. These braids increase our understanding of how the warps of triaxial weaves will behave at the selvedges.

In the Mexican double braid, Fig. 6, not only does the yarn rotate as in the previous examples, two layers of rotating yarn interact. The interaction of the layers inhibits the slipping and pulling of ends that cause one direction of yarn to dominate in the previous braids, resulting in a balanced plain or tabby weave. In Fig. 6B, it is clear that pairs of yarn cross as in Figs. 2B and 2C.

The Mexican double braid also begins at one contact point. It and the other braids shown are worked diagonally, parallel to the initial rows, slanting away from the contact point at the rod. This is not conducive to row-by-row weaving of triaxial works. All of the yarn in cord belt braiding (Fig. 7), however, begins at once in a row across the top. Pairs of dark yarn move initially towards

*Instructions for the braids shown are widely available. See bibliography.
the left, crossing pairs of light yarn moving towards the right. Each color folds itself under the
selvages to reverse direction, forming the same zigzag diagonal pattern that is clear in Fig. 18.

Braiding in rows controls the tension and spacing of the yarn for a compact and balanced weave,
a very desirable feature for triaxial weaving as well.

Other flat braids, somewhat complex, can illuminate further the configuration of selvages and
help us understand the manner in which a diagonally traversing and rotating weft must be
manipulated for triaxial weaving -- or more accurately, triaxial braiding -- by hand. The
examples shown, however, were the most helpful in developing the technique described in the
remainder of this article.

2. Triaxial Braiding

It requires only a slight adjustment in the movements of one's hands and fingers to incorporate a
warp into the diagonal manipulation of yarn, especially when the mechanics of the loom make a shed
in the warp, advance the finished cloth, and regulate the spacing of the warp and the beating of the
weft. Any unmodified standard handloom can be used for triaxial braiding.

Figs. 8A, 8B, and 9 show how to set up a loom for triaxial braiding. Fig. 8A shows one warp rod,
which corresponds to the rod normally used for the warp, and two additional rods for the weft.
The loops of cord (knots not shown for clarity), L and L', are added in stages to be described. These
secure the warp and weft rods to the metal rod m, attached to the cloth of the cloth beam, b.

Fig. 8B shows the warp threads through the heddles, indicated at h, and the reed. The warp is
ready to be tied to the warp rod. The weft has been slipped onto the weft rods and a third of them
have been spaced and secured in position by loops 4, 5, and 6. Since all of the yarn used in the work
is present at this stage, attaching it all to one rod would crowd the yarn together and complicate the
first few rows of braiding. Using two extra rods for the weft instead of one makes it possible to wind
the weft just as a warp is wound. This creates a 'shed' in the weft which keeps the weft ends in the
correct sequence and makes it easier to space the weft ends.

Initially, only loops 2, 3, and L', which acts as a hinge, secure the weft rod to the loom. The
warp rod and the right guide cord g hold the weft rods in place. The weft slips onto the rods just as a
warp slips onto lease or cross sticks. As each pair of weft ends is positioned, it is separated from
the rest of the weft. Each end is wound into a butterfly such as the one shown in Fig 8B, and carefully
placed off to the right. Care here is very important. Tangling of the butterflies can be substantially
avoided if each butterfly is placed onto the one that preceded with care while braiding. When
several pairs have been positioned, loops 4, 5, and 6 are added to secure them. Loops 4 and 5 are
tightened to prevent the weft ends from slipping between the rods before the first row is braided.
Fig. 9 shows the warp tied onto the warp rod, the weft spaced and wound into butterflies and all of the loops in place. Each pair of warp ends is tied separately onto the warp rod, shown at ½, and the ends pushed down between the warp pairs out of the way, as shown at ⅓. The warp is thus properly spaced at the beginning. A structural feature of triaxial weaves is their resistance to unraveling. All of the yarn heads directly into the fabric. No lead or flap need be woven in before braiding, but an inch or two should be designed into the beginning and end. This extra length is enough to fold under and stitched down to secure the ends when the loom is removed from the loom.

Triaxial braiding is not, however, suitable for all triaxial weaves. Since there is no tension on the weft ends, the only thing holding them in place is the tightness of the weave. In open weaves, the ends slip uncontrollably. Even in the denser weaves described below it is necessary to pull the crimp out of the previous few rows by tugging the weft ends as each intersection is completed. A few rows back into the fabric the weft is secure and will not slip, but tugging the weft ends to secure the most recent rows leads to distortion, quite evident in Fig. 16. Use of the reed for beating combined with measuring and adjusting every few rows reduces the distortion.

Figs. 10 through 15 show how to braid six triaxial braids using the setup shown in Figs. 8 and 9. The last part of each figure shows the weave as it actually appears. The other drawings of each figure show the yarn thinned down enough to learn triaxial braiding by examining the structure of the weaves. In most cases, I have shown the weaves progressing row by row. With practice, often several of these rows can be combined for a braiding progression more like that shown in Fig. 15.

In all six weaves, there is one more weft end than there are warp ends. In those weaves in which the ends are paired, the weft has one more pair of ends than the warp. A straight 1-2 3 4 threading with a direct one-to-one tie-up allows for all of the threading needed for these weaves. The take-up in the weft is considerable, ranging from 15 to 25 percent, depending on the weave, weight of the yarn used, and how hard it is beaten down.

Fig. 10 shows a weave in which the warp and weft ends are paired.* The intersections are identical to those in Fig. 2C. The crossing of the weft pairs -- pairs 1-2 and 3-4 in Fig. 10A for example -- mimics the crossings found in the flat braids. The ends of each direction of yarn always pass alternately over and under the ends of the other two directions, making this weave less complicated to braid than it may appear. In this, as in all of the weaves, the rows are staggered.

*Variation numbers have been assigned in the order that the weaves are presented in several patents. [20,21,23]
Alternate warp pairs lie dormant in the first row. The dormant and active pairs reverse roles in the second row, Fig. 10B. Fig. 10C shows how the selvedges are secured. The selvedges present the greatest difficulty in triaxial braiding, sometimes involving as many as three separate configurations before they repeat. In this weave, however, all the selvedge intersections are identical to each other and to the rest of the intersections in the weave.

Fig. 11 shows a closely related weave in which the ends are also paired. Here, though, the weft passes under the warp only when traversing from the left to the right. From right to left, the weft always passes over the warp, but the crossing of weft pairs remains the same. Since the weft moving initially from right to left is not anchored behind the warp as in Fig. 10, the ends should be wrapped about the inactive warp pairs of the first row as shown in Fig. 11A, or brought up from beneath the warp rod as shown in Fig. 11B. This same technique is used in several of the weaves shown. Fig. 11C shows that the left selvedge of this weave is more complex than the selvages in Fig. 10. The lower end of each weft pair reverses and re-enters the fabric without passing around a warp end. Care must be taken to avoid displacing the other weft ends that hold it in place. The right selvedge is much simpler and more secure. Both selvages repeat the same configuration at each reversal of a weft pair. The weft dominates the front of this weave. Conversely, the warp dominates the back.

The addition of a pair of warp ends through the crossings of the wefts between the warp ends in Fig. 18 gives us a weave structurally similar to that shown in Fig. 12. The extra pair fills the gaps between the original warp ends but are structurally unnecessary. The warp ends of this weave do not interact at all. When traversing from right to left, each end always passes over the weft ends traversing from left to right and under the structurally active warp ends (ends a, d, g, j, m, and p).

Though this is the reverse of Fig. 18, the essential relationship is the same. The selvedges in this weave fold under on the right and over on the left, closely resembling the selvedges of the flat braids illustrated above. The configuration remains the same at each reversal of a weft end.

The weave shown in Fig. 13 has paired warp ends and single weft ends, thus Fig. 13A shows alternate dormant pairs of warp ends rather than dormant single ends. The weft ends traversing from right to left alternately pass always over or always under the warp ends. The weft ends traversing from left to right secure them by passing over and under alternate warp pairs. Fig. 13B shows weft ends 2 and 4 folding under the warp pairs a-b and q-c respectively, but in Fig. 13C, weft ends 4 and 7 come from below and fold over the same warp pairs. An odd number of warp pairs assures a symmetrical alternation of these two selvedge configurations.

Figs. 14 and 14(a) show a weave with a more complex selvedge sequence. When moving from right to left, the weft ends always pass over the weft ends moving from left to right. Each leftward
traversing weft end passes under one and over two warp ends (Figs. 14A and 14B) before beginning a new sequence (Fig. 14C). Therefore, weft end 2 emerges from under warp end a at the left selvedge and weft ends 4 and 5 emerge from over warp end a. Weft end 8 again emerges from below, as shown in Fig. 14(a), thus beginning a repeat of the sequence. The weft ends traversing from left to right behave in the opposite manner. Since the pattern repeat of the wefts in this weave incorporates three warp ends, the total number of warp ends must be divisible by three for the selvedge sequence to work smoothly. This divisibility by three is also a factor in frame braiding, a flat braid not illustrated here [5].

Lastly, the weave shown in Fig. 15, the most difficult of all the weaves shown, also has a selvedge sequence consisting of three configurations. As in Figs. 14 and 14(a), the sequence repeats more smoothly when the total number of warp ends is divisible by three because, similarly, the weft ends incorporate three warp ends in their sequence. The weft ends traversing from left to right always pass under two weft ends coming from the left and under one warp end, then over one left-to-right weft end and over two warp ends. When the weft ends traverse from left to right, their behavior reverses: under one right-to-left weft end, under two warp ends and over the next two right-to-left weft ends and over a third warp end. I have shown the weave without regard to the total count of warp ends to show that it is possible, though awkward, to use other means of reversing the weft at the selvedge. The left selvedge in Figs. 15(b) and 15(c) repeats three configurations. Weft end 2 raids up over warp end a while weft ends 4 and 5 fold down and under warp end a. In Fig. 15(c), weft end 8 is positioned to start the sequence over. Weft end 7 at the right selvedge, however, must be squared down to fold over weft end 8 securely. This knocks weft end 7 out of sequence. Another method, not shown, is to hook weft ends around one another. Both methods leave lumpy, uneven selvedges, as shown in the right selvedge of Fig. 15(d).

To conclude, Figs. 16 and 17 show works completed using the triaxial braiding technique outlined in this article. Both employ the weave shown in Fig. 10 and demonstrate the potential of the technique for producing dynamic, sizable works using triaxial weaves and the unique color and textural qualities they offer. Obviously, since each intersection of the traversing wefts and incorporated warps must be braided individually -- as knots in rya must be tied individually -- this isn't a fast technique. The works shown are spaced at seven ends per inch, warp and weft, and took about as much time to produce as a tapestry of comparable size. As mentioned above, tangling of the weft ends is not a great problem if care is taken to place them off to one side after each intersection, but in larger works the size of the butterflies could become a problem.

Triaxial braiding isn't, then, a technique suitable for weaving yardage. For that, we must wait for a loom that mechanically manipulates diagonally traversing warp elements so that a weft can be passed quickly through a shed from selvedge to selvedge. For the purpose of using triaxial weaves to produce viable, single edition artworks, however, the technique works.
BIBLIOGRAPHY OF BRAIDING TECHNIQUES

Sources Consulted


ADDITIONAL REFERENCES


Pittsburgh, PA
FIG. 1 THE BASIC TRIAXIAL WEAVE:
A. Woven with diagonally traversing warp ends.
B. Woven with diagonally traversing weft ends.
FIG. 3 DIAGONAL BRAID (Peruvian belt braid).
FIG. 4 DIAGONAL BRAID, detail. Ends spread apart to show structure of the braid.
FIG. 8 DRESSING THE LOOM.
A. One warp, two weft rods.
B. Warp threaded, weft partially spaced and ready.
FIG. 9 DRESSING THE LOOM.
Warp tied on, weft spaced, rods secured.
FIG. 14 SIXTEENTH VARIATION.
A. 1st row.  B. 2nd row, left selvedge.  C. 3rd row, right selvedge.  D. 2nd & 3rd left selvedge configurations
FIG. 14(a) SIXTEENTH VARIATION.
E. 2nd & 3rd right selvedge configurations.
F. Appearance of weave.
FIG. 15 SIXTH VARIATION, 1st, 2nd left and last right selvedge configurations.
A: 1st row, 3rd left, 2nd, 4th right selvedge configurations.
B: 2nd row, 2nd left, 3rd right selvedge configurations.
C: 3rd row, 3rd left, 2nd, 4th right selvedge configurations.