TRIAXIAL WEAVES AND WEAVING: AN EXPLORATION FOR HAND WEAVERS

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Figure 1A shows the three axes of yarn that give this weave and its 23 variations the name triaxial (three axes) weaving. As opposed to the biaxial 90 degree interaction of conventional weaves (fig. 1B), three axes of yarn lock in three-way 60 degree intersections. This creates, as tests on industrial fabrics have verified*, a stable, isotropic fabric without a weak bias direction (fig. 1E). Triaxial weaves resist tearing and deformations common in biaxial weaves (fig. 1C–E). Further, the triangulated structure of the weaves helps dissipate impacts and loads, and accepts compound curvature with little distortion.

Developed in the 1960's by Norris Dow to solve the structural failure of fabrics used in the paragliders NASA designed to glide Gemini space capsules to earth [38], the properties of triaxial weaves allow industry to use fabrics lighter and more flexible than biaxial fabrics of equal strength† for applications ranging from balloons [1], space suits [12], and radome covers [44] to power transmission belts [81], nose cones [50,p.327], and bullet-resistant clothing [57,p.28]. Undoubtedly consumer products will follow [38, p.51], [56], taking advantage of physical as well as decorative properties [59, p.59], [38, p.3]—the same decorative properties that will certainly attract hand weavers to triaxial weaves because the third axis of yarn is a third axis of color, a third axis of texture, increasing infinitely the design challenges fiber offers to artists.

But how can hand weavers explore this potential? A loom that weaves triaxial fabric must not only advance the warp and finished cloth, form a shed, insert the weft, and beat the weft in, but, as shown schematically in

* For examples, see [20], [47], [48], [49], [50], [52], and [53].
† The question of defining equivalency between biaxial and triaxial fabrics is discussed in several of the testing articles cited above.

FIG 1: A. TRIAXIAL  B. BIAXIAL  C-E. BIAXIAL DEFORMATIONS
fig. 2A, must circulate the warp and maintain a constant warp length, shift laterally across the face of the fabric two opposing, traversing warp sets (the x and y warp sets in fig. 1A and figs. 3–26), transfer each warp strand to the opposite warp set as it reaches the selvage, and beat-up the fabric without interfering with the lateral shifting of the two warp sets. The textile industry has such a loom, the Barber-Colman TW 2006, but while its elegance, efficiency, and high production rate may fascinate us, the loom far exceeds the needs of hand weavers. Will the rich variety and ancient use of triaxial weaves in folk arts help? There hand weavers will find the comfort of materials in hand, manageable techniques, and human production rates. But although such techniques as sprang, cane weaving, and braiding use diagonal elements, and weaves such as leno, gauze weaves, and some surface techniques temporarily displace warp strands, hand weavers will find no means to sit down and weave triaxial fabric. Rather it is within the confluence of the ancient with the experimental, the merging of these disparate traditions, that weavers must seek those means.

THE WEAVES

Figures 3–26 represent 19 patented weaves [17], [18], and [28] and five additional weaves found in basketry. The variation numbers of the patented weaves have been assigned in the order that the weaves are presented in the patents with the patents in order by date of issue. For comparison, the weaves are presented in structural groups according to the manner in which the two warp sets interact. Examining each figure from the bottom, the x warp set, black, always traverses from the lower left to the upper right, the y warp set, cross-hatched, always traverses from the lower right to the upper left, and the weft set, stippled, weaves through the warp sets horizontally. The top center of each figure shows how the warp sets interact. The upper corners show the weft strands interacting with the y warp set on the left and the x warp set on the right. The central trapezoid of each figure shows the triaxially woven interaction of all three yarn sets.

GROUP A

In the first group of weaves (A), the warp sets do not interact. One
FIG 2: A. LOOM REQUIREMENTS  B. WARP TRAVERSAL
set always passes over the other set. Included are figures 3–10 and 23; the
basic weave, variations 8, 10, 12–16, and a modified 8th variation found in
basketry.

Basic Weave (fig. 3)

In this most fundamental triaxial weave the weft set always passes
under the x warp set and over the y warp set, thus locking all three directions
of yarn together. Since no two sets of yarn are interwoven, the fabric will
collapse with the removal of any one yarn set. In folk arts around the world,
the basic weave is used in baskets (figs. 27 and 28A-B) and other implements
woven with basketry techniques*, the lacing of snowshoes (figs. 29 and 30)
[43], [62, various pp.] and [11], lacrosse rackets [58, pp.123–131], [37, p.39],
etc. The commonly used half stitch of bobbin lace (fig. 31) [14, pp.609–610
and 627–629], [6, pp.234–235] and [30, pp.32–33 and 64–68] is the basic weave.
Several contemporary fiber artists use the basic weave (fig. 33) [4, p.62] and
[27, p.23], most notably Sherri Smith [8, p.11 and back cover], [21, p.66] and
[27, p.112].

8th and modified 8th variations (figs. 4 and 23)

An additional pair of weft strands passes, and closes the spaces, between
the locking weft strands of the basic weave. A modified version in which
one instead of two extra weft strands are added to the basic weave (fig. 23)
is found in baskets from South America†. The single strand divides the open
hexagon of the basic weave into two trapezoids.

10th variation (fig. 5)

This weave is identical to the basic weave except that every third strand
is removed from each yarn set. The paired strands tend to spread apart,
distributing the yarn evenly throughout the fabric. But here, as in other weaves
subject to slippage, stabilized selvedges hold the yarn strands in place.

* For examples, see [33, pp. 15–31], [26, various pages], [31, various pages],
[36, plate X], [37, pp. 58–59], [39, pp. 207–212], [40, p.377 and plate 172],
[45, pp. 56 and 158-160], [46, various pages, especially 140–143, 322–329,
337–344, and 379–377] and [54, p. 76].

† For examples, see [40, pp. 488–489 and plate 240], [46, p.141] and [5, p.217].

13
11th and 13th variations (figs. 6 and 7)

All three yarn sets are doubled in these two variations and the passage of the weft strands through the warp sets forms long floats of yarn. Not locked by any of the yarn sets, the strands do slip. These and other "unlocked" weaves can be beaten closer together than shown, often to the point of covering one yarn set. Conversely, the yarn sets may be spread further apart.

14th variation (fig. 8)

Again in this weave, which Dow named the "bi-satin weave", all three yarn sets are doubled, but here the paired yarn sets do not behave as a unit. The weft set locks the three sets together creating, in contrast to the 12th and 13th variations, an isometrically stable fabric with reduced slippage that retains the desirable design feature of long floats in the x and y warp sets.

15th and 16th variations (figs. 9 and 10)

Because it can be viewed as two basic weaves woven together, Dow named the 15th variation the "double basic weave". Beginning at the lower left corner with the first x and y warp strands and traveling to the right, skipping every second warp strand of each warp set, the first weft strand passes over all y warp strands and under all x warp strands, as in the basic weave.

Quite similar to the 15th variation, Dow named the 16th variation the "substrate weave" because of its potential use as the substrate fabric of molded composites.

GROUP B

Including figures 11-13 and 24, variations 4, 5, 11, and a modified 17th variation found in basketry, one strand of the first warp set of each weave of group B of the weaves always passes over strands of the second warp set. These alternate with strands of the first warp set that always pass under the second warp set. Although no more complex than some of the weaves of group A, this rather simple interaction of the warp sets, as well as the more complex interactions in groups C to E, changes the relationship of weft to warp sets and complicates the criteria for designing a loom. Weavers will appreciate that bringing the third yarn set to the surface of the fabric.
vastly increases the design potential of the weaves in these groups.

4th variation (fig. 11)

The y warp set in this variation is doubled while the x warp set is in single strands. The weft set, also in single strands, splits the doubled y warp set. To remedy possible slippage, Dow suggests the periodic insertion of a second weft strand, w'. Secure selvedges eliminate the need for an extra weft strand, though it is an interesting design feature.

5th variation (fig. 12)

Similar to the 4th variation, the y warp set is doubled, but here the x warp set and the weft set are also doubled.

11th variation (fig. 13)

Here the warp strands are single while the weft strands are paired. Note that every second x warp strand is hidden from view.

Modified 7th variation (fig. 24)

Found in South America [46, p.141], this weave differs from the 17th variation (fig. 17) only in the omission of every second y warp strand. This creates an unusual asymmetric variation.

GROUP C

The warp sets of the weaves in group C interact in a tabby or plain weave pattern. Included are figures 14-17 and 22; variations 1-3, 17, and a modified 1st variation found in basketry.

1st and modified 1st variations (figs. 14 and 22)

Considering the single warp set strands as a tabby weave deformed 30 degrees from its normal 90 degree orientation, this weave can be understood as a tabby weave with doubled yarn strands slipped through the overlapping, tabby-woven elements.

A modified version, found in baskets from the Philippines [3, pp.317-318], uses a single rather than doubled weft strands (fig. 22)

The interwoven warp sets confine slippage in the 1st variation to a
FIG 13: 11TH VARIATION
lateral movement of the weft pairs. Dow suggests a periodic locking weft, \( w' \), to tighten the weave and reduce this movement.

2nd variation (fig. 15)

Here paired yarn sets interact in a more complex and thoroughly locked manner than in any of the weaves described so far. Note the illusion that the weft strands run from the lower left to the upper right.

3rd variation (fig. 16)

Similar to the second variation in its stability and doubled yarn sets, this weave provides fascinating possibilities in the pinwheel effect at the three-way intersections of the yarn sets.

17th variation (fig. 17)

Less complex than the previous two weaves, the yarn sets of the 17th variation, found in baskets from the Far East to South America*, are not paired and the interaction among them is much simpler. This weave could be woven tighter or looser than shown, but is shown in this porous spacing to reflect Kaye's intention that her weave be used as an embroidery canvas that allows variations in stitching impossible with orthogonal canvases [29].

GROUP D

The warp sets of the weaves in group D intersect in various twill patterns. Included are figures 18–21; variations 6, 7, 9, and 18.

6th variation (fig. 18)

Consider the endless possibilities suggested by the illusion of a surface composed of tiny cubes. Native to Malaysia, where it is understandably known as "mad weaving", anyam gila, this variation is found in baskets as far west as India.+

* For examples, see [3, pp. 318-319], [36, plates VI, IX, XI, and XII], [45, p.78] and [46, pp.111, 327–329, and various plates].

+ For examples, see [3, pp. 324-325], [23, pp. 111–112, which include well illustrated instructions for plaiting a basket with this weave], [39] and [46, pp. 160–162 and 165].
7th variation (fig. 19)

Considerably easier than the 6th variation, the first weft strand of each pair, \( w' \), can be viewed as an extra locking weft such as those found in figures 11 and 14, although in this case its omission definitely promotes slippage. Further, these locking weft strands also stabilize the spacing of the yarn sets.

9th variation (fig. 20)

Here the weft, hidden from view, serves only to stabilize and regulate the spacing of the twill weave of the warp sets. By using a variety of yarn weights, however, the weft becomes an active design factor of this warp-faced triaxial weave.

18th variation (fig. 21)

This variation shares a weft sequence similar to Kaye’s other weave (fig. 17), and, similarly, the yarn strands can be spaced closer together or farther apart than shown.

GROUP E

Duplicate and triplicate plait basket weaves (figs. 25 and 26).

Some of the warp strands of the basket weaves of group E, the duplicate and triplicate plaits found in South America (45,p.141), pass always over or always under stands of the opposing set while other stands of the warp sets weave together in tabby or twill weaves, thus removing these weaves from any one structural category. This doubling and tripling of strands in spaced groups suggests a whole range of possibilities not found among the patented weaves.

WEAVING

Triaxial frame loom (fig. 32)

All works executed on the frame loom shown in figure 32 are accomplished painstakingly with a tapestry needle. Rooted in techniques and ideas found in basketry and snowshoe lacing, the frame loom is the only method that accommodates all triaxial weaves.

Figure 27 is a triaxially woven basket from China. Figures 28A-B show
FIG 18: 6TH VARIATION
FIG 24: MODIFIED 17TH VARIATION
FIGURE 27

Triaxially woven basket from mainland China.
Photographed by the author.
spiral and circular weft insertions, stippled, typical of such baskets [46, pp. 323 and 327]. Basket weaving is the most direct form of triaxial weaving and the techniques provide an idea important for weaving triaxial works on a frame loom — start in the center, blackened strands in figure 28A–B, and work out towards the selvedges, represented by the cross-hatched boundaries of the bases of the baskets. Weaving from the center out not only makes starting pieces easier, but reduces distortion. Subsequent strand pairs are woven in as numbered in figure 32. The ends are tied onto the dowel rod, which are attached to turnbuckles, t. The turnbuckles control the tension of the yarn sets. The resulting triaxially woven area is a hexagon, but by selectively not interweaving yarn sets, triangular, rhomboid, and trapezoid works are possible. Since no yarn set reverses itself, as in the fabric shown in figure 2B, works produced on a frame are open systems. This allows weavers to design infinitely unfolding radiating designs such as that shown in figure 33.

Figure 28C shows how warp strands may fold over the top border of a basket and weave back down into the sides, in this case to complete a basket woven in the 17th variation (fig. 17). [5, pp. 217–218 and plate CII]. This suggests a method of finishing works woven on a frame loom.

In its use of a frame and pliable rawhide "yarn", called babiche [37, p. 62], snowshoe lacing offers an immediately accessible means of weaving triaxial works by hand. Figure 30 shows how the Ojibwa lace snowshoes [43, pp. 150–151]. The Ojibwa and other snowshoe makers use a single strand of babiche, which is a drawback. Shown loosely woven and crimped to trace its course, the babiche is actually pulled tight as in figure 29. The Ojibwa lash the babiche around the frame, as yarn is initially lashed around the frame loom, shown in the inset of figure 32. Other Indians, however, bore holes through the frame [43, p. 42] or use a selvedge thong secured along the inside of the frame [11, p. 17].

While valuable for exploring and understanding the weaves, then, and able to produce credible small works, the frame loom is severely limited. Weaving the three yarn sets together with a tapestry needle is inefficient, limited, and tedious as would be weaving conventional pattern weaves on a rectangular frame.

* For additional illustrations of techniques used to weave a wide variety of basket styles, see [3], [5], [7], [39], and [46].
FIG 28:  
A. BASKET, SPIRALING WEFT  
B. CIRCULAR WEFT  
C. BORDER  
D. CANE WEAVING
FIGURE 29
Triaxially laced snowshoe. Photograph provided by Vermont Tubbs, Inc. (snowshoe makers)
Forestdate, VT 05745.
FIG 30: LACING AN OJIBWA SNOWSHOE
From: Osgood, William and Leslie Hurley. The Snowshoe
Book. 2nd ed. Battleboro, VT: Stephen Greene
permission.
Looking further into folk arts, the half stitch of bobbin lace, fully described in available sources [5, pp. 234–235] and [30, pp. 52–53 and 54–58], is equivalent to the basic weave. Figure 31 shows its use in portions of two bookmarks. The half stitch is the closest the folk arts get to triaxial fabric, but the time and impossible number of bobbins required to weave a piece of fabric of any size, plus the absence of tension and of any way to beat the yarn into a tight fabric, limits the attraction of bobbin lace as a method of weaving triaxial works.

Finally, though triaxial works as such do not occur in braiding by hand, braiding techniques do use diagonal elements and, sometimes, a third set of yarn serves as a core around which the diagonal sets are woven [2, pp. 56–69], [15]. Industry has begun to examine braiding as an alternative approach to triaxial weaving [51]. This is an area that deserves further attention.

Figure 2A shows, schematically, the requirements for a loom designed to weave triaxial fabrics. The warp must rotate (fig. 2A(1) and (2)) to accommodate the lateral shifting of the two warp sets in opposite directions (fig. 2A(5)). Since, in most looms, the warp strands go from a circular array to two flat sheets, as shown at the top of figure 2B, the distance from the warp supply component to the fabric varies as the warp rotates. This requires a warp length compensator (fig. 2A(2)). Finally, the loom must transfer the warp strand at the end of one warp set to the beginning of the opposing warp set after each lateral shift (fig. 2A(6)). During these rotating, shifting, and transferring motions, the loom must still perform the conventional functions of forming a shed (fig. 2A(4)). Inserting the weft, and beating the new weft strand against the fell line, the leading edge of the fabric.

In 1881, Malhère designed a machine that duplicated the movements of hands, fingers, pins, and bobbins to produce machine made bobbin lace. As this includes the half stitch (basic weave), Malhère's machine was the first capable of weaving triaxial fabric [41]. But the loom's complexity — four Jacquard mechanisms driving hundreds of moveable tubes, weights, discs, pegs, levers, etc. all spread over two floors and producing a strip of lace only a few inches wide — is such that contemporary authors recognized its impracticability [42, p. 188]. Though important as the first machine to weave triaxial fabric, triaxial weaving is incidental to its main purpose. Malhère's machine offers nothing towards the realization of a versatile handloom.

Components of several other looms are, however, quite useful, both
FIGURE 31

Bobbin lace half stitch (basic weave) used in two bookmarks (detail). Note how the weave works at angles other than 60 degrees.
Samples supplied by Cynthia Williams.
Photographed by the author.
FIG 32: TRIAXIAL FRAME LOOM
Figure 33

Mogen David (detail).
Wool mounted on wood. Yarn in all three directions
approximately 8 epi. Collection of the Columbia Health Center,
Pittsburgh.
Woven and photographed by the author.
to further weaver's understanding of the requirements for a triaxial loom and to provide an inventory of alternative ways those requirements may be met in a handloom. Therefore, in the remainder of this article I will describe the components of several industrial looms, two experimental looms, and one handloom, and will conclude with a speculative design for a handloom that borrows from several of these looms. The components are arranged according to the functional requirements of a triaxial loom. Interested readers should refer to the sources cited below for full technical descriptions.

The industrial looms are Heathcoat's 1809 bobbin traverse machine [22, pp. 189-201] and Brown's 1811 traverse warp machine [22, pp. 218-221], both designed to weave lace netting, Crompton's 1895 cane weaving loom [10], designed to weave chair seats in the weave shown in figure 28D, and Stewart's 1921 lateral shifting and warp transfer system [54a]. The last industrial loom, the Barber-Colman TW 2000, originally patented in 1972 by Norris Dow [57, p.28], is the only industrial loom that produces true triaxially woven fabric. The two experimental looms, built in the late 1960's and early 1970's to supply fabric samples for testing and to test loom designs, are the Proesco hooked-heddle loom [20], and Fabric Research Laboratory's (FRL's) cam roll loom [52]. The handloom is the Gloor Tri-Weaver, patented in 1979 [24] and [25].

Warp feed, warp rotation, and warp length compensation

The looms can be divided into two types: (1) those in which each warp strand is wound onto a separate warp carrier which is then itself maneuvered by the loom's mechanisms; and (2) those which separate the warp supply component from the lateral shifting and transferring functions.

Heathcoat, Crompton, and Gloor employ warp carriers, shown in figure 34. Since each carrier itself rotates about the weaving mechanism and feeds an individual warp strand into the fabric, these looms require no separate warp feed, rotation, and length compensation components.

In Brown's warp traverse, vertically arrayed machine, the two warp sets are wound in two layers onto the upper beam, which is one half as long

* Since this loom has undergone continuous refinement, several patents must be consulted for a thorough description: Warp feed and length compensation, [68], heddle design [32], shed formation [31], lateral shifting [34], warp transfer [35] and [55] and beat-up, [16]. In addition, some good descriptive articles have been published, for example, [9] and [59].
FIG. 34: WARP REELS
A. HEATHCOAT
B. CROMPTON
C. GLOOR
as the width of the finished lace. Rotation of this beam about its axis feeds the warp strands down through the weaving mechanism where they are secured onto the lower beam. A circular plate equal in diameter to the length of the upper beam is interposed between the upper beam and the stationary bobbins that supply the third yarn set. Strands of one warp set pass through holes drilled around the circumference of the front half of the circular plate. The other warp set passes through holes along the back edge of the plate. The plate, which rides on casters set into a circular track, rotates in unison with the beam to circulate the warp strands. From the plate, the warp sets diverge, spread out to the width of the finished lace by dividers set between the circular plate and the bobbins. Strands from one warp set fill the "even" spaces of the divider and strands from the other set fill the "odd" spaces. From here, the warp strands continue down to interact with the yarn set carried by the bobbins.

Shown schematically in figure 2A, the warp strands of the Barber-Colman TW 2000 are wound onto several short beams arranged in a circle, end to end, on a reel set on top of the loom. The reel, like Brown's circular place, rides on wheels set into the frame of the loom. From the beams, the warp strands pass through tension control devices and over and through a ring set concentrically inside the reel level with the surrounding warp beams. The warp strands turn down and pass over a warp length compensator mathematically calculated to offset the variable distances from the circular ring above it down through the warp carrier blocks below it. From the carrier blocks, the strands descend into the weaving mechanism as two parallel warp sets.

The Prodesco loom also feeds warp strands from a reel through a warp rotation mechanism that flattens the strands into two warp sets. The warp strands of FRL's cam roll loom, a vertical loom in which the finished fabric winds onto the upper beam, are individually weighted, borrowing from the ancient warp-weighted technique. The strands therefore rotate freely as the loom laterally shifts the warp sets.

Shed formation and weft insertion

Heddles project from the warp carriers of the Glore and Crompton looms (fig. 34). In both looms, the carriers ride on tracks on either side of the weaving plane, one track for each warp set, with the carrier heddles of
each warp set projecting towards those of the other. Gloor's warp sets descend vertically towards the fell line with the warp carrier tracks in front of and behind the warp strands. Crompton's warp carrier tracks are above and below a horizontal weaving plane. The shedding mechanism of each loom moves the warp carrier tracks towards one another, a movement which extends the projecting heddles past one another to form a countermarch shed. Both looms, and all of the other looms except Heathcoat's and Brown's, use a rapier weft inserter.

The warp carriers on Heathcoat’s loom, however, do not have heddles projecting from them (fig. 34). This reflects the purpose of the loom—to weave bobbin net lace, not fabric. Bobbin lace is formed by combinations of the cross and the twist [30, pp. 50–51]. The cross corresponds to the lateral shifting of warp sets in triaxial weaving, but the twist, in which one yarn strand wraps or twists about another, is unique to bobbin lace. The warp carriers must be free to twist the diagonally traversing yarn strands about the stationary longitudinal yarn set that runs from the lower to the upper beam. (Since it is strung from beam to beam as on a conventional loom, this longitudinal yarn set could be called the warp. This suggests that triaxial weaves can be conceived of as having a single warp set with two diagonally traversing and interweaving weft sets—a view that could radically alter loom designs.) Heddles would impede this twisting movement. The shed is formed, then, not by moving the carrier tracks towards one another but by sliding the carriers off the tracks onto a comb and moving them between longitudinal yarn strands. In this way the yarn carriers, more properly called bobbins, “...can be made to move like so many clock pendulums...through the longitudinal or beam threads.” [22, p. 198] Half of the carriers slide from front to back while the other half, carrying the opposing warp set, slide from back to front.

Carriers have the advantage of avoiding warp feed, rotation, and warp length compensation problems, but their width can be reduced just so much. Carriers thus space yarn too far apart to weave fine fabrics successfully. Crompton’s loom weaves cane in a rather open weave (fig. 28D), so the carriers work well*. Heathcoat managed to weave lace at 16 epi, but only by staggering his bobbins in two rows, which greatly complicated his loom [22, p.192]. Gloor’s loom can weave conventional fabrics at 14 epi, but the warp carriers limit

* Contemporary fiber artist Tammy Kulamor has successfully used this weave in her work [27, p.53].
triaxial fabric to "...7 warp intertwines per inch." [25, p.3] Stewart, in a 1921 patent for a woven fabric that contains diagonal elements, suggests a solution that would enable a loom to produce triaxial fabrics in a much closer weave [54a].

Stewart devised an oval track (fig. 35A) the long sides of which project the heddles of each yarn set towards one another. It forms a countermarch shed by extending the heddles in a manner resembling the extension of warp carrier heddles on the Gloor and Crompton looms. The spacing of yarn, then, is restricted only by the width of the heddles and the weight of the yarn, as in conventional weaving.

Shed formation in the Barber-Colman loom, shown both in figure 2A and 35B, works in a similar manner, but the key to shed formation, lateral shifting, and warp transfer in this loom lies in the design of the heddle. As shown in figure 2A, the rear end of each heddle is higher than the projecting front end. The high ends ride in grooves cut perpendicularly through an inner stationary bar positioned above the heddles and shed formation mechanism. These grooves are aligned with similar grooves cut into adjacent outer bars. When in their retracted position as shown as (4) in figure 2A, the high ends of the heddles rest in the outer tracks, which laterally shift the heddles. When extended forward by the shed forming bar, the heddles rest in the grooves of the inner stationary bars, allowing the outer bars to reset for the next lateral shift. Thus the shed formation and lateral shifting of the heddles are linked by the design of the heddles.

The Prodesco hooked-needle heddle loom separates the warp rotation and the lateral shifting of the warp strands from the heddles, whose only function is shed formation. In order for the warp strands to shift and transfer, they must be disengaged from the fixed hooked-needle heddles, and herein, literally, lies the snag of this loom design. The weaver must (1) shift the warp sets so that the heddles, arranged in two opposite rows, may extend into the area between the warp sets; (2) shift the warp sets back so that the heddles may extend further, beyond the warp set furthest from it; and (3) shift the warp sets again to position them for capture by the retracting hooks. The retracting hooks capture the warp strands and pull them back past the strands of the opposing warp set to form the shed.

FRL's cam roll loom differs significantly from the others. The cam roll, which combines the shed formation and lateral shifting functions, resembles the yarn tracking systems used in braiding machines [13]. Below
FIG 35:  A STEWART: SHED, WARP SHIFT AND TRANSFER  
B. BARBER-COLMAN: DOUBLE BEATER, SHED
the cam roll a horizontally placed cylindrical roll separates the individually 
weighted warp strands into two sets and also forces the strands into the threads 
of two horizontally mounted indexing screws. Placed above the warp separating 
roll and below the cam roll, the two screws, one for each warp set, turn in 
opposite directions to shift the warp strands laterally through the cam roll. 
In the cam roll, large cams with two slots in each set at 45 degrees from 
one another alternate with smaller unslotted cams. Every second small cam 
is drilled off center so that as the cam roll rotates, the off center cams move 
alternating warp strands backwards and forwards. Those strands resting on 
the concentrically drilled cams remain stationary. Thus a shed is formed.

Lateral shifting of opposing warp sets

All triaxial weaves are characterized by two opposing yarn sets, designa-
ted x and y warp sets in figures 3-26, that traverse through the fabric 
diagonally in opposite directions. Looms accomplish this lateral movement 
in three ways: (1) by sliding warp carriers or heddles along tracks (Heathcoat, 
Crompton, Stewart, and Barber-Colman); (2) with indexing screws (FEL's 
cam roll loom and Gloer); or (3) by disengaging the warp sets from heddles 
(Procesco) or yarn spacers (Brown) and shifting them independently.

The same tracks used to form sheds in the Crompton loom and in Stewart's 
system also provide the means of shifting each warp set one space, in opposite 
directions, after each shed formation. Since Crompton's warp carrier heddles 
(fig. 34B) and Stewart's heddles (fig. 35A), in their retracted positions, do 
not interfere with each other, they are free to shift along their tracks.

As shown above, the heddles of the Barber-Colman loom rest in grooves 
cut into stationary inner bars when extended to form a shed and retract back 
into a second set of grooves cut into adjacent outer bars. The outer bars 
shift the warp sets one space over in opposite directions. When the shed forming 
mechanism again extends the heddles into the grooves of the inner bars, the 
outer bars reset to receive the retracting heddles for the next lateral shift.

Heathcoat's loom is similar except that entire warp carriers rather 
than heddles leave the laterally shifting bars, called conducting bars by 
Heathcoat, and move forward onto the teeth of a comb as described above. 
While the carriers are on the comb the conducting bars reset to receive the 
carriers and laterally shift the carriers of each yarn set one space over in 
opposite directions.
Both Gloor and FRL's cam roll loom use indexing screws to laterally shift the warp sets, but in wholly different ways. Gloor's warp carriers rest in the grooves of a spacer, shown at a in figure 34C. Pins extend down from the spacers into the teeth of indexing screws, i. Each warp set has its own indexing screw. When retracted, as shown, the carrier heddles are free to shift. By turning each screw in opposite directions, the weaver can laterally shift each warp set one space, but Gloor's hand operated loom, the only handloom currently available, gives the weaver freedom to turn either or both indexing screws in either direction or not at all. Gloor's loom thus allows artists to design works in which diagonally traversing yarn sets change directions, oscillate, or do not shift at all, thus providing tremendous versatility but at the price of requiring the weaver's intervention at many stages of the weaving process.

FRL's cam roll loom combines shed formation and lateral shifting functions in the design of the cams in the cam roll, as previously described. As the two screws below the cam roll rotate they pull the warp sets sideways into the slots of the larger cams. The positions of the slots force strands of one warp set into one set of slots and strands of the other warp set into the other set of slots so that the strands of both warp sets shift laterally, in opposite directions, through the cam roll without interfering with each other.

The warp sets of Brown's loom extend down from the perforated circular plate below the upper beam into dividers, as described previously. The dividers are stationary so the warp strands must be disengaged from them to shift laterally into the next divider space. Brown accomplishes this with two sets of forked pins. Short pins of one set alternate with longer pins of the other set. The difference in length prevents tangling of the warp sets as the forked pins push the warp strands out of the divider spaces, shift them one space in opposite directions, and place them into the next divider spaces.

Similarly, the warp strands of the Prodesco loom must disengage from fixed hooked-needle heddles in order to shift laterally. Between sheds, the heddles disengage themselves from the warp strands and retract out of the way. There being no automatic stops or other mechanical means of positioning the warp strands on this loom, the weaver rotates and positions the creel and warp advance mechanism by eye to shift the disengaged warp sets in opposite directions.
Warp strand transfer

With each lateral shift of the warp sets, the end strand of each warp set reaches the selvedge and must transfer to the beginning of the opposing warp set, as shown at (6) in figure 2A. The removal of a strand from one end of the warp set leaves a space at the other end for receipt of a strand from the opposing warp set. Looms accomplish the transfer by (1) transferring a disengaged warp strand (Prodesco and FRL's cam roll loom) or disengaged warp carrier (Gloor) by hand; (2) mechanically transferring warp carriers (Crompton); or (3) mechanically transferring heddles (Stewart and Barber-Colman).

When a warp strand shifts into its final position in the Prodesco loom, the weaver transfers the disengaged warp strand by hand to the initial position in the opposing warp set. Similarly, in FRL’s cam roll loom, the weaver removes the end-most strand from the cam roll, one from each end, and moves them outside of the indexing screws, rests them in the beginning of the screw opposite the one each has left, and sets them back into the cam roll. The strands now go through the roll as members of the warp set opposite the warp set they came from.

In Gloor’s loom the weaver transfers an entire warp carrier. The weaver must tilt the loom to bring the warp carriers up and forward towards the weaver. The weaver then removes the end-most warp carrier, and its warp strand, of each warp set and places each at the beginning of the opposing warp set.

When a warp carrier in Crompton’s loom reaches the final position on its track, an electromagnet pulls the carrier off the track and slides it onto a transferrrer. The transferrrer pivots and positions the carrier adjacent to the beginning of the opposing track. The new carrier is then pushed from the transferrrer onto the track.

As shown in figure 35A, when in their retracted positions, the heddle tracks of Stewart’s system are aligned with semicircular continuations of the tracks. The transferring mechanism slides the end-most heddle of each warp set around to the beginning of the opposite track as shown. This system is flawed, however, in that as the heddle transfers it pulls the warp strand out of alignment by the distance d.
The Barber-Colman loom combines elements from Stewart and Crompton to transfer each heddle efficiently without pulling the warp strand out of alignment. When a heddle reaches its final position at the selvedge and the shedding mechanism extends it forward, rather than sliding into another groove of the inner stationary bar it slides into a receptacle in the heddle transferring mechanism. The transferrer swings the high rear end of the heddle in an arc to the receiving end of the opposing heddle shifting and shed forming mechanisms. The notch on the rear of the heddle, shown at (4) in figure 2A, slips from a projection on the shedding mechanism onto a similarly shaped projection on the flattened arc of the transferring mechanism. This flattened pathway forces the heddle to slide forward as it is transferred just enough to keep the eye of the heddle in alignment with the rest of the warp strands. At the receiving end, the notch on the heddle engages the projection on the shed forming bar. The shed forming bar then retracts the heddle from the transferrer.

Beat-up

As in conventional weaving, each new weft strand must be beaten against the fell line, but a closed reed would prevent the warp sets from shifting laterally. Beaters on triaxial looms, therefore, must be open on one side to allow the teeth to retract from between the warp strands. Bobbin lace is not beaten, so neither Heathcoat nor Brown provide beaters on their looms. With the exception of FRL’s cam roll loom, in which the weaver uses the hand inserted rapier to beat the weft in while the cam roll holds the warp strands in position, the other looms use retractable beaters.

In Crompton’s loom, a bar with strong upright pins moves up between the warp strands to beat the weft against the fell line. Since the warp strands shift laterally as the beater moves forward, the beater cannot retreat along the same path. Instead, it drops straight down and moves away from the fell line while in this lowered position.

Crompton’s loom needs only a single beater because the structure of cane weaving (fig. 28D) holds the laterally shifted warp sets in position when the beater retracts. In triaxial weaves, however, something must hold the traversing yarn sets in place during the next shed formation and lateral shift. This requires at least two beaters: one to hold the warp sets in place as the
second pushes the new cross of the shifted warp sets and the new weft strand to the fell line. The first beater must retract just before the second hits the fell line.

Figure 35B shows the Barber-Colman double beater system. Rotating cams, indicated at c, time this delicate ballet of beaters as various levers and pivots move each beater along a path p. The path of one beater is the reverse of the other. As shown, each beater retracts straight back and away from the fell line to move up into beating position without interfering with the lateral shifting of the warp sets. Gloor employs a double beater system similar to Barber-Colman's except that the weaver uses levers to manipulate the beaters by hand. In principle, the Prodesco loom is the same except that the beaters are combs unattached to the loom. The weaver inserts and removes them by hand.

Speculative loom design (fig. 36)*

Figure 36A shows, schematically, a speculative design for a handloom that employs ideas from the looms described above and offers an alternative to Gloor's loom. A creel, c, on which are mounted individual warp spools and individual tension control springs, t, rotates the warp strands and feeds them from the rear of the loom over a warp separator, s, into the weaving mechanism. The rectangular separator divides the circle of warp strands into x and y warp sets. Open-ended heddles, h, shown in detail at C, not unlike Brown's forced pins, engage and extend strands of each warp set past one another to form a countermarch shed. Weft strands may be inserted in any conventional manner.

Once the weft strand has been inserted, one beater, b, of a double beater system that could be made similar to that shown in figure 35B, pushes the new weft strand against the fell line and remains in place, as described above, until the second beater advances towards the fell line. Dow has suggested, however, that it may be possible to avoid a complex double beater system in a handloom based on this design. Proper alignment of the front yarn guide, e, would hold the warp strands in place as a single beater is withdrawn and

* This design, based on the model prototype of the industrial loom patented by Norris Dow, has been drawn from sketches and suggestions provided in correspondence from Mr. Dow. For additional details of a similar creel, see [19]. For a general discussion of loom requirements, see [20].
FIG 36:  
A. SCHEMATIC SIDE VIEW  B. YARN GUIDES  
C. HEDDLES  D. YARN IN YARN GUIDES
repositioned to beat in the next weft strand.

Two sets of saw-toothed warp strand guides, g, rest in front of and behind the heddles. The spacing of the teeth matches the spacing of the heddles and the teeth of the beaters. The front spacers have extended guides attached to every second saw-tooth, shown in detail B. The tension springs and separator force the warp strands into the guides. The guides regulate the spacing of the warp strands and provide the means of laterally shifting the warp sets. When the heddles retract, the warp strands rest in the guides, as shown at D. The guides now shift the warp sets laterally in opposite directions. When the heddles extend and engage the warp strands to form a shed, they disengage the warp strands from the guides so that the guides can reset for the next shift. A transferrer, not shown, slips the end-most strand of each warp set around the separator to the beginning of the opposing warp set after each lateral shift.

For ease of operation, this design requires, at minimum, mechanical synchronization of creel rotation, lateral shifting, and warp strand transfer functions with the shed forming mechanism. Hand weavers would then only have to form the shed, insert the weft, and beat the weft in to weave triaxial works with motions identical to those of conventional hand weaving.

As the textile industry adds consumer products to the current technological uses of triaxial fabrics, hand weavers will undoubtedly awaken to the virtually unexplored artistic potential suggested by the variety of relationships among the three yarn sets in the 23 weaves presented here—color and textural relationships impossible with conventional weaves.

Traditional uses in folk arts increase hand weavers' appreciation of the potential of triaxial weaves and offer some clues towards ways of weaving them. But though Gloor's loom can produce the basic weave and the loom design described above would produce the basic and double basic weaves, thus providing useful means of advancing from the tedious method of weaving on a frame, no handloom or industrial loom currently produces works in a wide range of the weaves presented in this article. The possibility of such a loom is an open question—would it be too complex to be practical, like Malhère's machine?—but an investigation of how existing looms have met the requirements of triaxial weaving provides a rich inventory of mechanisms to work with as demand for a versatile handloom develops.
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