Andrew Glassner's Notebook

http://www.glassner.com

Digital Weaving, Part 1

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Woven cloth is so common these days that many of us take it for granted. But even a moment's examination of an everyday cloth like denim reveals some beautiful patterns.

Weavers create cloth on a mechanical device called a *loom*. In this column, I'll describe enough of the basics of weaving so that next time we can write a loom-simulator program. My motivation, as in several of my previous columns, is to discover new ways to create attractive visual patterns. Of course, nothing can beat actually going out and creating real, woven fabrics. The goal isn't to replace weaving, but to use the ideas of weaving to create software tools for making patterns.

Others have already brought together computers and weaving. In the "Further Reading" sidebar I've identified several commercial programs designed to help weavers. They're often complex and reward advanced knowledge of weaving. There's also an interesting weaving language built into the art program Painter (manufactured by Procreate), which I'll talk about in the next issue.

The first thread

In terms of their complexity, looms are similar to old sailing ships: the basic ideas are simple, but the actual implementation can be complex. One reason for this complexity is the quest for simple creature comforts. Weavers often spend many continuous hours working at a loom, so a lot of effort has gone into comfort and labor-saving mechanisms to make the job as pleasant as possible. Although you can build a simple loom with almost no moving parts, most modern looms are formidable machines.

In this section, I'll simplify and abstract a loom's structure so that we can ultimately capture its essence in a computer program. I'll speak of "threads" and "fabrics" in this discussion, though modern looms can weave all sorts of things—from thick, fuzzy yarns to wide, satin ribbons and everything in between.

At its heart, a loom is a machine that interleaves two sets of perpendicular threads. In one common format, one set of threads extends directly away from your body, and the others run left-to-right.

Figure 1 shows a simplified loom. The red fibers that go out away from us are called the *warp threads*, and they're strung and held taut through mechanical devices called *shafts*. The blue horizontal fibers are called the *weft threads*, and they're strung and held taut through devices called *treadles*.

Setting up a loom is kind of like writing a program, and indeed some people cite the task of setting up a Jacquard loom as the birth of programming. Jacquard looms could produce extremely intricate designs by reading weaving instructions from a deck of punch cards, which embodied the weaver's design. By loading up the loom with a different type of thread, the loom could produce a different fabric from the same basic pattern.

Three fundamental types of basic weaves exist—the plain, satin, and twill—which give rise to endless variations and combinations.

The most common is the *plain weave* (Figure 2a). In this pattern, each weft thread goes over and under each warp thread, in perfect alternation. Plain weaves are often used for clothing. An interesting variation is oxford cloth, which is often used for work shirts. Here each weft thread is actually doubled up, so although the pattern is still square there's double frequency in the weft direction. This produces a durable yet attractive finish. You may also recognize the plain weave as the central element, or *plait,* of a classic Celtic knotwork panel. I've discussed this in my three-part "Celtic Knotwork" column (starting with the September/October 1999 issue of *IEEE Computer Graphics and Applications*).

Another common pattern is the *satin weave*. In this style, the weft threads pass over several warp threads before they pass under one (Figure 2b). Weavers stagger the interlaces so that no two overlaps are adjacent. Typically the warp threads are thin, and the weft threads

1 A schematic version of a simple loom. The shafts along the bottom deliver the red vertical warp threads. The treadles on the right deliver the blue horizontal weft threads.

Treadles

Shafts
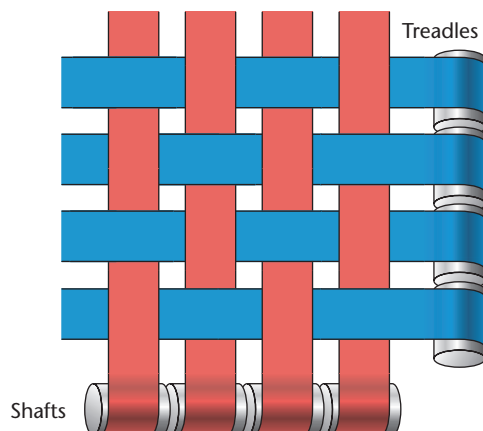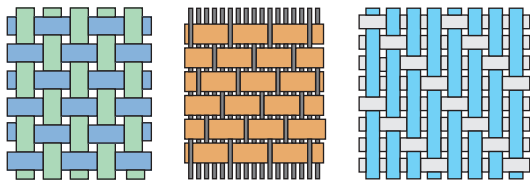
2 Three basic weaves: (a) plain, (b) satin, and (c) twill.

are wide, smooth, shiny, and closely packed. This gives the fabric a smooth and luxurious look and feel.

The third common pattern is the *twill* weave, shown in Figure 2c. Twills are like satins, but differ in three respects:

- they often don't exaggerate the difference between wide and narrow threads like a satin,
- threads don't usually pass over as many threads before they pass under again, and
- sometimes the warp threads pass over several weft threads.

Twills are easy to spot because of their distinctive diagonal component. As opposed to a satin weave, where the interlaces aren't adjacent, in most twills each thread starts one step to the left or right of the one above it, creating the diagonal. Perhaps the most common twill used today is denim. If you look closely at your favorite blue jeans you'll see the diagonals formed by the blue and white threads.

Now that we have some basics under our belts, let's look at how to describe a weave.

A rough draft

The basic pen-and-paper schematic for setting up a loom is called a *draft*. A draft has three parts:

- the warp threads' setup,
- the weft threads' setup, and
- something called the *tie-up*, which we'll get to in a moment.

The ability to read a draft is essential to understanding existing patterns and creating new ones. Fortunately, it's a pretty straightforward process.

A basic draft is no more than four simple black-and-white grids. This technique was originally developed for hand-drawing and hand-copying drafts, because it's easy and fast to draw. It's also great for black-and-white photocopying. Although color and computer tools are both becoming more common, the black-and-white draft remains popular for many weavers.

Although a black-and-white draft is convenient for doodling out a new design, I found that originally learning to read drafts in this form was a little difficult. Because I have the luxury of using color in this column, I'll augment the traditional black-and-white drafts with a colored and threaded version that I hope will make the pattern easier to visualize. I'll use greenish threads for the warp and ochre for the weft.

Further Reading

I found a good introduction to drafts and weaving in *Designing and Drafting for Handweavers*.[1] An online glossary for basic terms can be found at http://www.initco.net/~elh/glossary.htm.

The painting program, Painter 7—published by Procreate (http://www.procreate.com)—has had a weaving language built into it for quite a while. It lets you design your own weaves and then use them as patterns for filling. Their weaving language, however, can be tricky to use (I'll have more to say about it next time).

There are a variety of commercial and public-domain programs available to weavers. I haven't used any of these programs myself. Some of the better-known programs include

- Fiberworks (http://www.fiberworks-pcw.com),
- Patternland (http://www.mhsoft.com),
- Swiftweave (http://www.swiftweave.com),
- WeaveIt (http://www.weaveit.com),
- WeaveMaker (http://www.weavemaker.com), and
- WeavePoint (http://www.weavepoint.com).

As a result of this commercial development, there's now a standard file format for descriptions of weavings. It's called WIF (the Weaving Information File), and it seems to be pretty stable (the most recept specification of it that I can find is dated 1997). You can read about the WIF format at http://www.mhsoft.com/wif/wif.html.

You can find some nice drafts at http://www.wyellowstone.com/users/ww/weaving.htm and http://www.allfiberarts.com/cs/patternsdrafts.htm. Also, there are many books full of great patterns. Two books that I found useful were *The Key to Weaving*,[2] and *A Weaver's Book of 8-Shaft Patterns*.[3]

References

1. B. Frey, *Designing and Drafting for Handweavers*, Macmillan, Basingstoke Hampshire, England, 1958.
2. M.E. Black, *The Key to Weaving,* Hungry Minds, Hoboken, N.J., 1980.
3. *A Weaver's Book of 8-Shaft Patterns*, Carol Strickler, ed., Interweave Press, 1991.
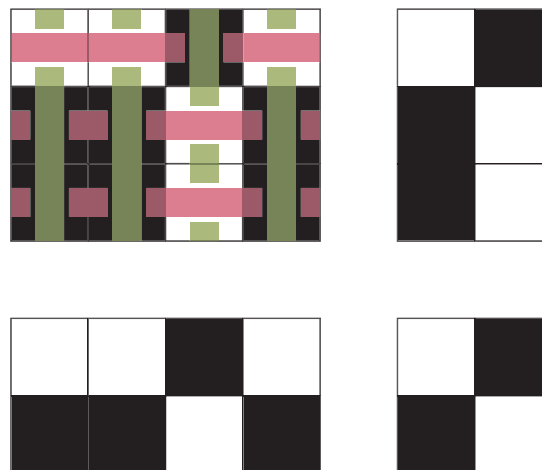
3 A simple draft.

Take a look at Figure 3, which shows a simple draft. The draft has four sections, each one a small grid separated from the others with a bit of white space.

4 Colors indicating particular cells from Figure 3.

5 A taller version of Figure 3 with a different weft pattern.
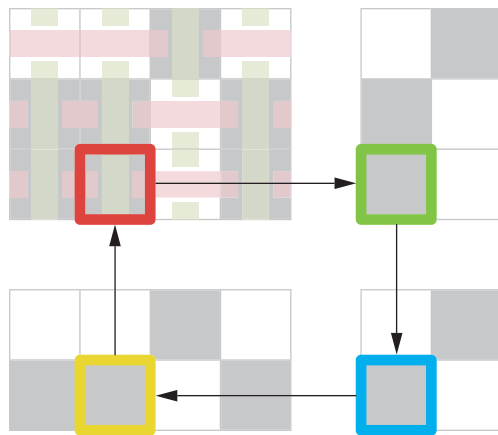
In the lower left is the warp threading's definition, in the upper right is the weft treadling's definition, and in the lower-right is the tie-up. These three grids describe how to set up the loom to weave fabric. The grid in the upper-left shows the fabric that results from the other three grids. In this picture of the fabric, a black cell means that the warp thread is on top, while a white cell means that the weft is on top (look at the colored fabric for clarification).

The layout of these four grids is by no means standardized. Sometimes you see the warp threads at the top rather than the bottom, or the weft threads on the left rather than the right, or both. The layout I'm using here is fairly common. It's not too hard to convert a draft in any format into this one; after a little experience you'll be able to do it by eye.

Let's now focus on the three lower right grids and see how they specify the fabric in the upper left.

I'll look first at the warp pattern in the bottom left. It states that our fabric will be only four threads wide. Actually, it states that the *pattern* is only four threads wide; we can repeat this pattern over and over horizontally if we want to make a wider fabric, simply by appending copies of the pattern to the left as many times as we need.

The black cells in this grid tell us when to place the warp thread over the weft thread. In this draft, there are two rows to the threading pattern, so there are two ways to weave the weft threads into the warp threads. If we use the pattern on the bottom row, then the weft threads are instructed to go under all but the second warp thread from the right. If we choose the upper pattern, then the weft threads go over all the warps threads except the second one from the right.

Which of these two patterns do we use for any given weft thread? The answer starts in the upper-right of the draft, where the weft pattern is given. We can see that only three weft threads are defined, so we're going to create a tiny bit of fabric only four threads wide by three high (again, we can repeat this three-thread pattern over and over if we want to create a taller piece of fabric).

Let's weave our fabric from the bottom up, so we'll start at the bottommost line of the fabric (that is, the lowest row of the upper left grid). Suppose we want to determine the color of the third cell from the right on
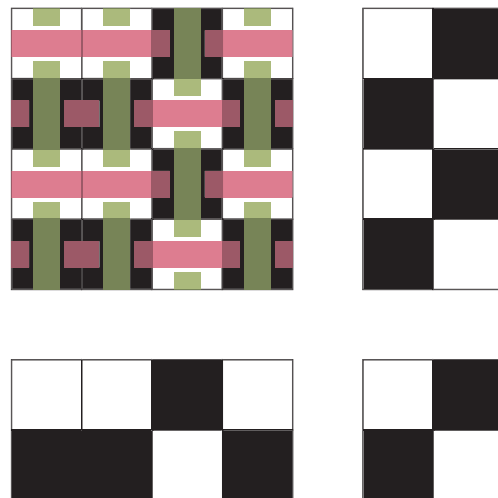
the bottom row, marked in red in Figure 4.

We look to the right of this cell to find the row of the weft pattern that corresponds to the row the cell is in. We're looking for a black cell (each row in the weft must have exactly one black cell). In this case, the cell in the leftmost column is filled in (I've marked that cell green in Figure 4). That tells us that this thread will be woven according to the instructions in the leftmost column of the tie-up.

The job of the tie-up is to tell us which of the warp rows to use when we weave a given weft thread. The tie-up is the grid in the bottom right. In this example, it's very simple. It has two columns (because the weft treadling has two columns) and two rows (because the warp threading has two rows).

Because the row we used from the weft treadling has a black cell in its left column, we're instructed to look for black cells in the left column of the tie-up. In that column, there's only one black cell, which I've marked in blue in Figure 4.
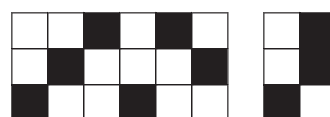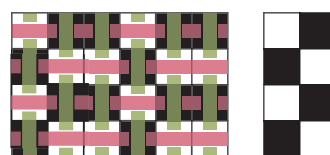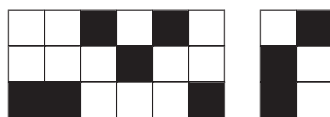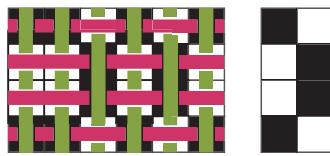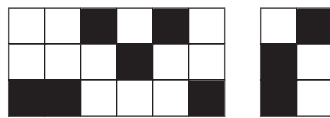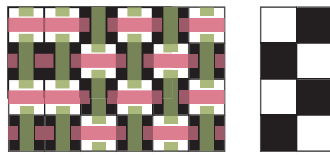
Now that we've found a black cell in that column of the tie-up, we look left to the corresponding row of the warp pattern and look for the entry below the cell with which we started. I've marked this warp cell in yellow in Figure 4. If that cell is black, then the warp thread in the red cell is on top, otherwise the weft thread is on top.

We fill in the entire fabric grid in this way, putting in a black cell everywhere a warp thread goes over a weft thread.

This description is almost complete, but I've left something out. I'll fix it in a moment, but for now, look through the rest of Figure 3. See if the resulting fabric pattern in the upper left makes sense to you.

For another mental workout, take a look at Figure 5— it shows the same warp and tie-up, but with a different weft pattern.

You can see how these three grids interact in Figure 6. Figure 6a shows a weaving that's six threads wide by three high. In Figure 6b I've changed only the weft pattern, and in Figure 6c I've put the weft pattern back but changed the warp and the tie-up.
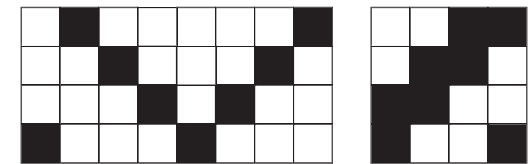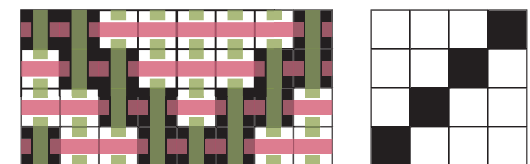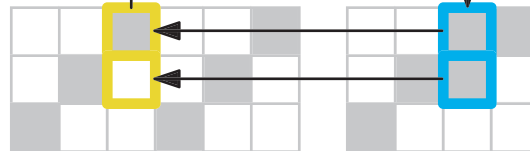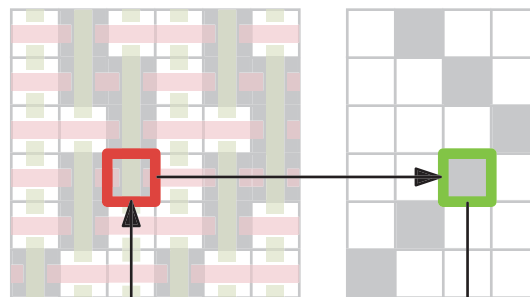
7 Three warp patterns can create four different rows of overlapping patterns, thanks to the tie-up.

8 Finding the color of a cell using the draft of Figure 7 and the coloring scheme of Figure 4.

6 (a) A draft. (b) Varying the weft pattern. (c) Varying the warp and the tie-up.

9 A small but practical draft.

Now let's make that fix I promised. I said that each row of the weft pattern must have exactly one black cell. Each column of the warp pattern must also have exactly one black cell. But, and this is the big one, the tie-up can be any combination of black-and-white cells that you care to create. Most importantly, each column can have any number of black cells, from none at all to a solid vertical column.

What does it mean if a column of the tie-up has two black cells? It tells us to use both indicated rows of the warp pattern. If either row has a black cell, then that cell of the fabric is black as well.

Look at Figure 7 to see an example of this. In Figure 8 I've followed one cell from the fabric using the same coloring scheme as in Figure 4. Starting with the red cell, we move right to the corresponding row of the weft pattern, where we find the green cell. Moving down to the tie-up, we find two black cells, both marked in blue. Thus we look left for each one to find the warp entries in both rows under the fabric's cell; I've marked these in yellow. In this case, the upper cell is black and the middle cell is
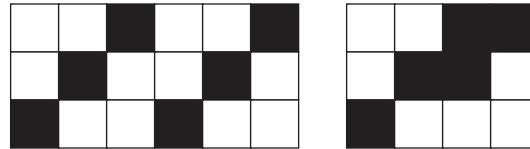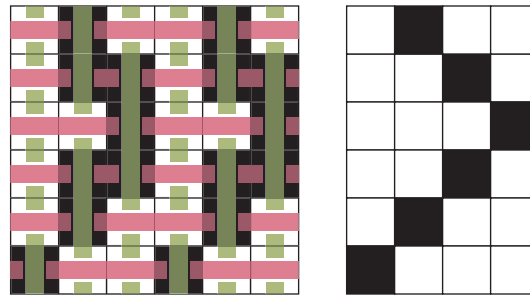
white. Because at least one of them is black, the corresponding fabric cell is black.

The big advance here is that the tie-up essentially lets us combine rows of the warp pattern without making the pattern bigger. In Figure 8, we have four different patterns (from the top, row 0, rows 0 and 1 together, row 1, and row 2). We could have made the warp grid taller by one and made a new row just for the combination of rows 0 and 1, but this form is more compact.
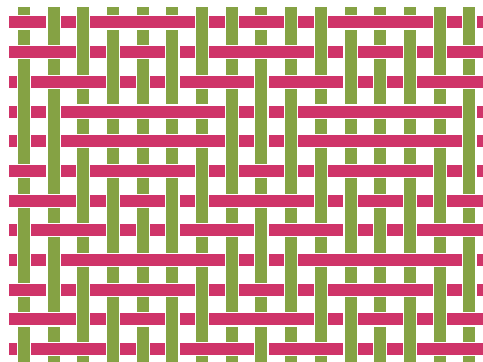
We can put this all together in Figure 9, which uses

10 A pattern made by repeating the sequences of Figure 9.

11 The coordinate systems used for a draft. Note that each of the four matrices uses a different system. In all cases, the first coordinate named is the vertical one, marked with a black arrowhead, and the second is horizontal, marked with a white arrowhead. The region marked *F* is the fabric, *S* marks the shafts (describing the warp threads), *R* marks the treadles (for the weft threads), and *T* identifies the tie-up matrix.

all the ideas we've seen so far. In Figure 10 I've made a larger piece of fabric simply by repeating the sequences of the draft.

Sometimes the drafts you see in books or online are given in a numerical form rather than picture form. It's not too hard to turn one into the other, as long as you remember where the origin for each pattern is located.

Although this numbering style also varies, Figure 11 shows the most common style that I've seen. The origin for each pattern is at the corner that they all share. The first coordinate counts vertically (up or down) from that point, and the second counts horizontally (left or right). Of course, this is a bit strange to get used to at first, but it becomes natural very quickly. Getting used to counting this way makes it easier to read the many drafts published on the Web and in books, because no matter where you put the pieces of the diagram, you always count outward from the shared corner, up, and then across.

Of course, some authors defy convention and count from the outside in, or horizontally first and then vertically. Generally it's worth a moment's thought to visualize where the origin is located before typing in a numerical draft that you get from someone else.

The weaving equation

Given the regularity of weaving and how the three grids (for warp, weft, and tie-up) look like matrices, I wondered if I could express the fabric grid mathematically.
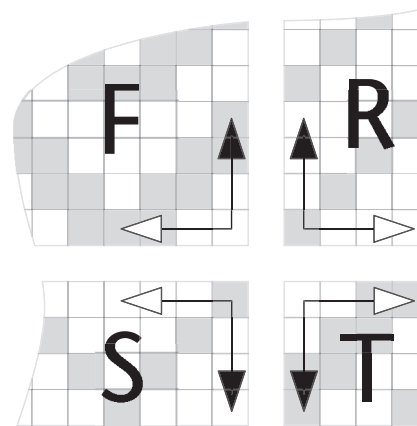
It's actually pretty easy. Figure 11 shows how I'll label the matrices and their coordinate systems.

We know which two threads intersect at any given cell $F_{y,x}$, so our goal is only to determine which one is on top. I'll say that a value of 0 in the matrix *F* means that the horizontal weft fiber is on top, and otherwise it's the warp. I'll start by initializing all the elements of the matrix *F* to zero.

Two important numbers are associated with each of the patterns: the number of threads, and the length of the repeat. For example, we might have a pattern like that in Figure 10. From its draft in Figure 9, we can see that there are four warp threads, and the pattern repeats every eight units. Similarly, there are four weft threads, and they repeat every four units.

For the shaft pattern *S*, I'll write *s* for the number of threads, and $\bar{s}$ for the length of the repeating sequence, and *r* and $\bar{r}$ for the threading. So in Figure 10, as in Figure 9, we have $s=4$, $\bar{s}=8$, $r=4$, and $\bar{r}=4$.

We'll index *F* by the values (y, x), measured from the

lower right of *F*. Our first step is to find out which row of the treadling sequence *R* is called for. Since the weft sequence has $\bar{r}$ elements, we want row $y' = \mod \bar{r}$ (recall that *a* mod *b* gives us the remainder of dividing *a* by *b*).

Now that we have the row, we look through it for the location of the one black cell—that is, the one containing the value 1. Let's say that's at position *c*, so that $R_{y,c} = R_{y',c} = 1$, and all other $R_{y,j} = 0$ for $j \neq c$.

This tells us that we want to look at column *c* of the tie-up. There might be several 1s in this column, so we need to look at each one in turn. So we'll consider elements $T_{k,c}$ for $k = [0, \bar{s}-1]$.

For each element in column *k* of *T*, we look at the corresponding warp thread pattern in *S* that's below *x*. Just as *y* might have been beyond the repeat length of the weft pattern, so might *x*, so we need to find $x' = x \mod \bar{s}$, which is the index of *x* inside the warp pattern.

So now we look at $S_{k,x'}$. If that's a 1, then the warp thread should be on top, and we add 1 to $F_{y,x}$. We then step to the next value of *k*, and then check the matrix *S* again, and so on, until we've taken care of all the rows.

The process matches the four arrows shown in Figures 4 and 8.

That's all there is to it! There's one little gotcha—each time we find a row that contributed to *F*, we added in 1. That means that some elements of *F* could have values as high as *s*. This isn't really a problem. We'll just say that a value of $F_{y,x} = 0$ means that the weft thread is on top and any other value places the warp thread on top.

We can summarize the whole job with a few equations. First we get the values of x' and y' corresponding to the respective entries of *x* and *y* in the basic patterns:

$$x' = x \mod \bar{s}$$
$$y' = y \mod \bar{r}$$

Now we just run through the algorithm:

$$F_{y,x} = \sum_{c=0}^{t-1} \sum_{k=0}^{s-1} R_{y',c}\, T_{k,c}\, S_{k,x'}$$

I call this the *weaving equation*. It nicely packages up the algorithm that a simple loom is implicitly using when it weaves a piece of cloth. Unlike some mathematical expressions of physical procedures, the process of evaluating the equation closely matches the real-world process. If you follow through the summation signs, you'll see that the equation is basically a mathematical mirror of my prose description.

Tightening up

Readers familiar with Boolean logic have probably already noted that the weaving equation is expressed as a sum of products. Digital engineers will recognize this as a standard form of logical expression. Computing simplified versions of sum-of-product expressions is possible using a graphical technique called *Karnaugh maps*, though the sheer number of terms in the weaving equation would make for a huge diagram.

The digital perspective gives us a way to write the weaving equation in a much simpler form. Think of the weft matrix R as a one-dimensional array $\hat{R}$ of decimal numbers. Index i in this array tells us the position of the single black cell in row i of R. Let's use the draft of Figure 7 as an example. In this draft, $\hat{R} = (0, 1, 2, 3, 2, 1)$. Of course, we're counting upward from the bottom of R, and assigning numbers left to right. Now let's think of the columns of the tie-up matrix as a one-dimensional array $\hat{T}$ of binary numbers. Taking each column from top to bottom, and reading the columns from left to right, the tie-up in Figure 7 gives us $\hat{T} = (001, 010, 110, 100)$. Finally, we'll think of the columns of the warp matrix S also in binary. Reading them top to bottom, right to left, we can create the one-dimensional array $\hat{S} = (100, 010, 001, 100, 110, 0010)$.

Now we can write the weaving equation more compactly. For a given cell $F_{y,x}$, we find the appropriate column of the tie-up to consult from $\hat{R}_{y'}$ (where I'm again using $y' = y \bmod \bar{r}$). Looking up that column in the array of binary numbers formed by the columns, the chosen column of the tie-up is just $\hat{T}_{\hat{R}_{y'}}$. We find the proper column from S as $\hat{S}_{x'}$. Now we'll compute the logical AND (written &) of these two binary numbers. If any of the 1s in one number lines up with any of the 1s in the other, the result of the AND will be nonzero.

Summarizing this symbolically, the simplified form of the weaving equation is just:

$$F_{y,x} = \hat{T}_{\hat{R}_{y'}} \ \& \ \hat{S}_{x'}$$

I like this result, because we've done away with both summations and gotten rid of a lot of overhead computation. We just look up a couple of numbers, compute their logical AND, and write that result into the fabric.

To see this equation in action, let's use it to evaluate the cell highlighted in Figure 8. We want $F_{3,2}$. We'll first note that the draft has a three-unit pattern for the warp, and a six-unit pattern for the weft. Thus, $y' = 2 \bmod 6 = 2$,

and $x' = 3 \bmod 3 = 0$. So $\hat{R}_{y'} = \hat{R}_2 = 2$, and this sends us to $\hat{T}_2 = 110$. We also have $\hat{S}_{x'} = \hat{S}_0 = 100$. Computing the logical AND of these two bit patterns gives us 110 & 100 = 100. This is the value for $F_{y,x}$, and because it's nonzero, we know that the warp is on top in that cell, as it's marked in the figure.

Decorated drafts

Now that we've got the basics of drafts in hand, we can decorate them to create even more interesting patterns.

The basic idea behind decorated drafts is to add thread information to the basic pattern. Threads have many properties—color, shininess, fuzziness, thickness, and so on. I decided to implement three of these qualities: color, thickness, and spacing.

To add color, we just name a color for each thread of the warp and weft. It's tempting to actually color in the cells in the warp and weft grids with the color of that thread, but that can make the draft harder to read (a light-yellow thread is almost impossible to make out against a white background). So weavers typically add an extra row (or column) outside of the draft that indicates the color for each thread, as in Figure 12a (next page).

In Figure 12a I've assigned a single color to all the warp threads and a different color to all the weft threads. In Figure 12b I've given each of these groups a repeating pair of colors. In Figure 12c I've assigned three colors to the warp pattern and five to the weft.

Adding thickness follows the same approach. To specify thickness I describe a thread's width with a number from 0 to 100, where 0 means it's invisibly thin, and 100 means it's as wide as the default cell size (of course, you could use actual dimensions like millimeters or inches instead). As with colors, you can give a single number for all the threads in the weft and warp (as in Figure 13a, next page) or give a list for each (as in Figure 13b). As with colors, these lists get reused when we reach the end. To save space, I left off the drafts from Figures 13, 14, and 15, since they're identical to that of Figure 12.

We can also control how much spacing appears between the threads. I use a number from 0 to 1, which gives a fraction of the thread width to appear as white space around it. A single number can apply to all the threads, as in Figure 14a (see page 115), or we can use a list that repeats, as in Figure 14b.

Because any of these lists can have any length, when we reach the end of a list, we just start reading values over again from the beginning. This applies equally well to the warp and weft patterns themselves, as well as the colors, thickness, and spacing information.

Figure 15 (page 115) shows an example of a weaving that uses variation in color, spacing, and thickness.

So now our basic repeating unit of fabric can be big. Recall that the warp pattern repeats every $\bar{s}$ threads, so a simple fabric would repeat horizontally every $\bar{s}$ threads as well. But if the warp's color pattern has a entries, and the thickness pattern has b entries, and the spacing pattern has c entries, then the horizontal width of the repeating unit of fabric will be the least common multiple of all four numbers. If the numbers are relatively prime, then even if they're all small the repeat can be large. For example, if $\bar{s} = 7$, $a = 3$, $b = 4$, and $c = 5$, then the fabric will have
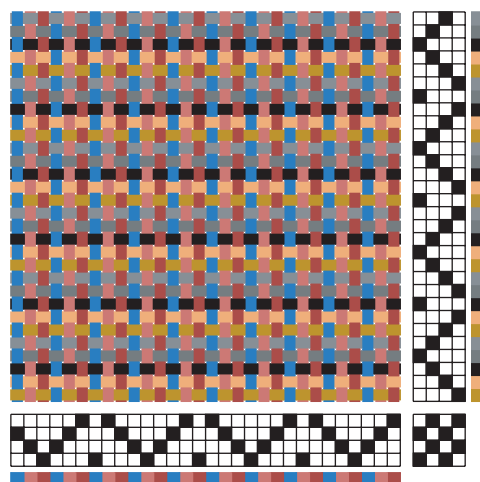
12 Adding color information to a draft. (a) The original weaving, using a single color each for the warp and weft. Both warp and weft patterns repeat every eight units. (b) The color patterns are each two threads long. (c) The weft color pattern has five entries, and the warp has three.
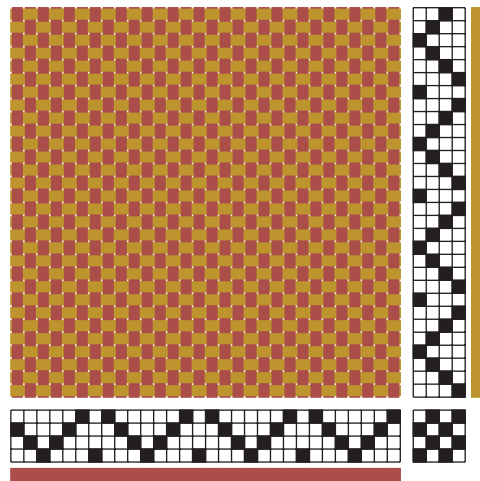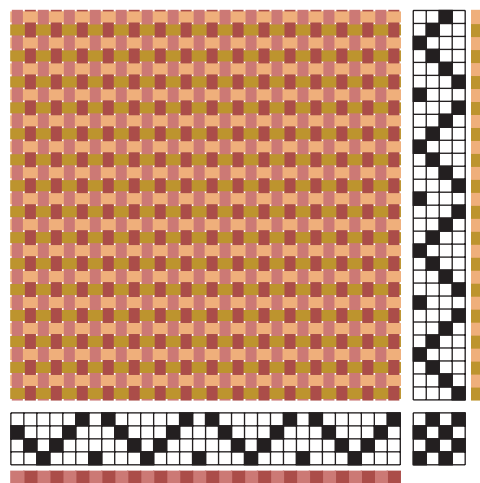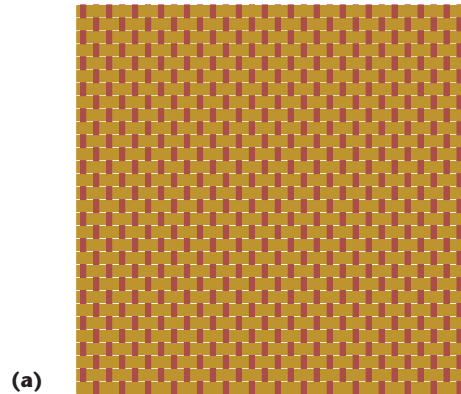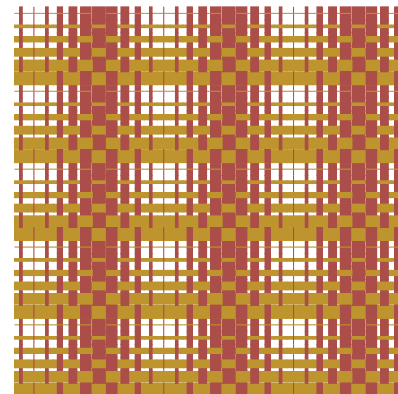

(a)

(b)

13 Adding thickness information to the draft of Figure 12a. (a) The thickness patterns have the same length as the warp and weft patterns. (b) The thickness patterns have different lengths.

Examples

Let's look at some examples of weaving based on these ideas.

I'll begin with a screen shot of my weaving design environment. Figure 16 shows my program in action. I used this program to interactively create all the woven fabric images in this column. I'll discuss this program, and how it was written, in more detail next time.

In the following examples, I've included the draft when I thought it was large enough to be both legible and interesting to see. In some of the larger weavings, the full draft would be so small compared to the fabric that it would be illegible if we printed it here.

Figure 17 shows a simple two-color twill. Note the diagonal pattern of that is characteristic of twills.

The *huck* pattern is a sort of fuzzy square. Figure 18 shows a checkerboard pattern composed on a variation of hucks. Figure 19 (see page 116) shows a large unit based on a huck. This draft uses eight threads in both the warp and weft, with a 30-unit repeating pattern. Figure 20 shows how it looks woven into a larger fabric. Figure 21 shows another variation on the huck, here used to make an op-art sort of design.

Weaving geometric patterns is another fun option. Figure 22 shows one way to make eight-pointed stars. Figure 23 shows a simple but attractive form of alternating diamonds.

a horizontal repeat of 420 threads. This is great news for those times when we want to generate big chunks of non-repeating texture. Remember, however, that much of the appeal of woven fabrics is in their repetition, so you'd want to keep these two opposing desires balanced.
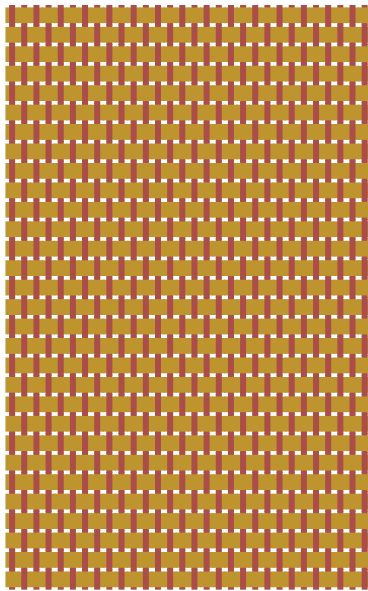
(a)
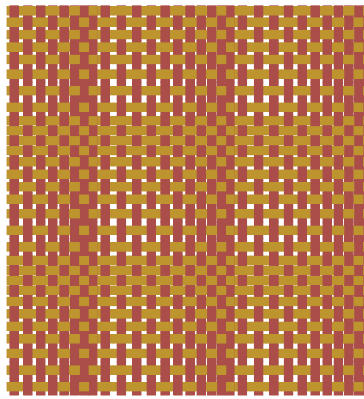
(b)

14 Adding spacing information to the draft of Figure 12a. (a) The spacing patterns are constant for the warp and weft. (b) The spacing patterns have different lengths.
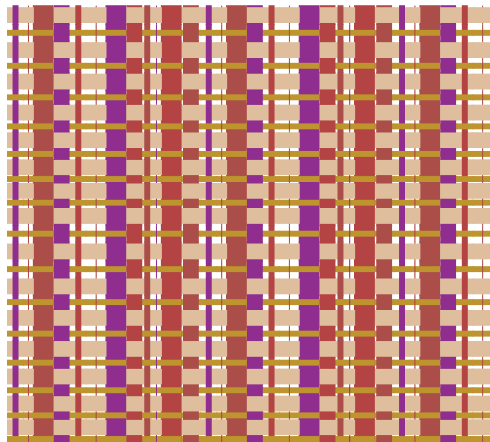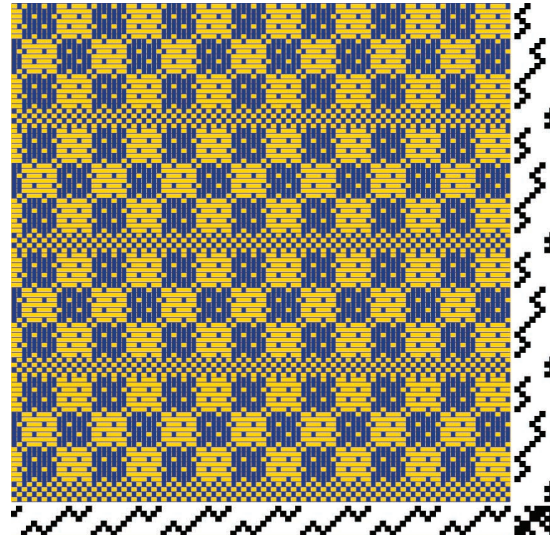

15 The draft of Figure 12a, augmented with changes in color, spacing, and thickness. The design is deliberately extreme so that each of these qualities can be easily seen.
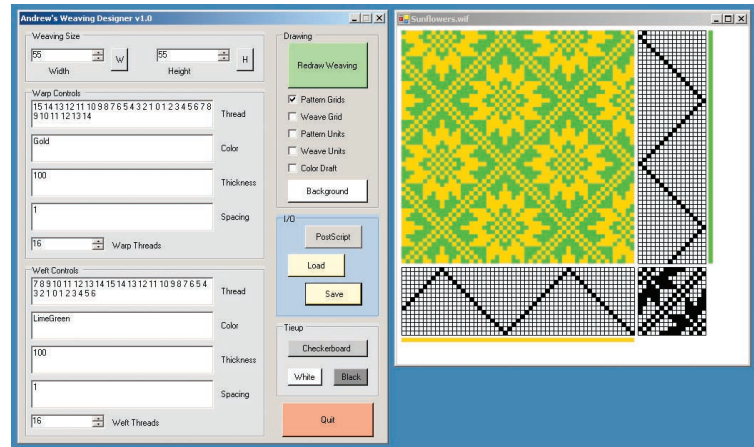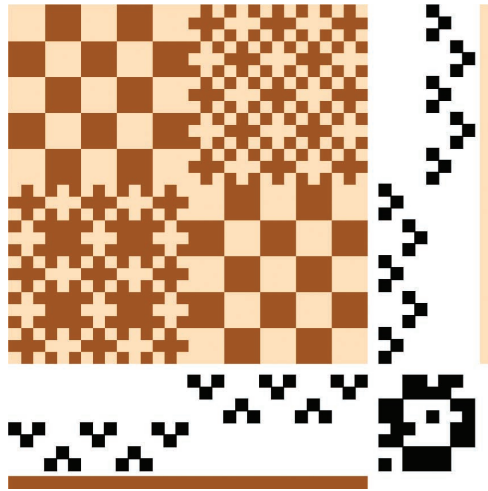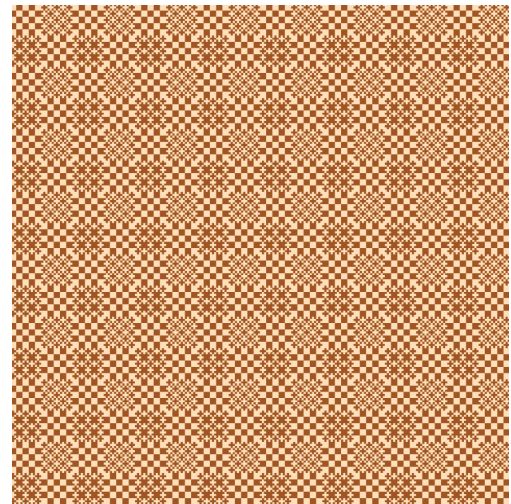

16 A screen shot of my digital loom.
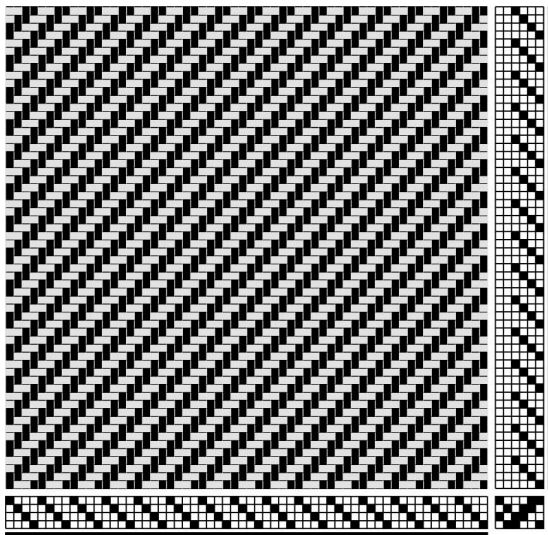
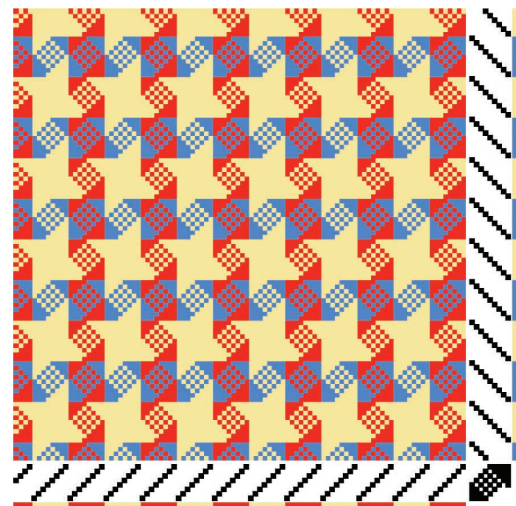**17** A simple two-color twill.

18 A two-color checkerboard pattern.

19 A unit for a weave based on the huck pattern (the draft is from http://www.allfiberarts.com/library/gallery/blma-babyhuck.htm).

20 Several units of Figure 19 woven together.

21 A two-color design based on a huck pattern.
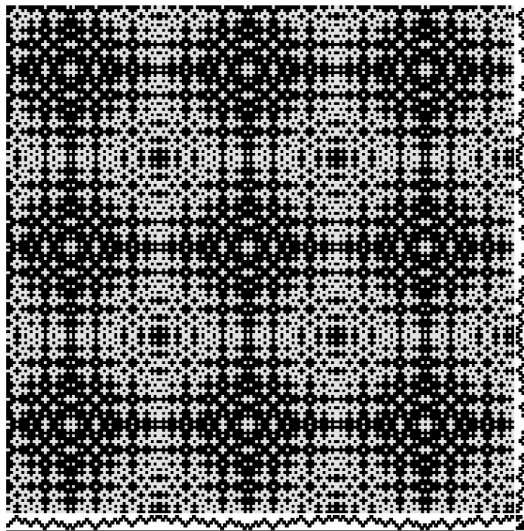
22 An eight-pointed star design (this draft came from http://www.allfiberarts.com/library/bldraft/blstars.htm).
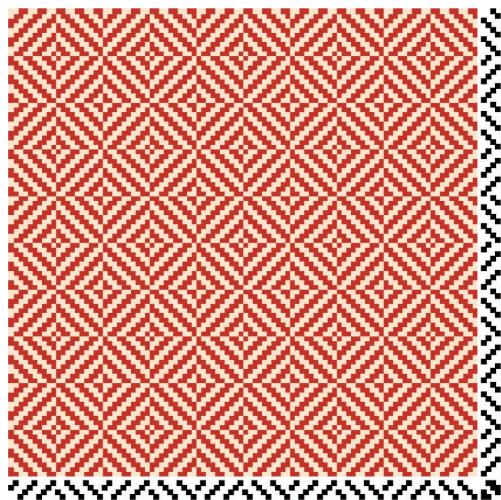
23 A simple but attractive "Norse Star" pattern (the draft is from http://www.geocities.com/EnchantedForest/1154/rweave.html).

Plaids are of course one of the most popular forms of woven fabrics. Figures 24 and 25 (see page 117) show two different plaids.

Seemingly simple units can lead to surprising results. Figure 26 shows a single unit known as a *cat's paw*. When we put a bunch of them together, as in Figure 27, we get a beautiful figure known as a *snail's trail*.

To show just how much the tie-up affects a design, the next few figures all use the same patterns in the warp and weft, and vary only in their tie-ups. Figure 28 shows a close-up of a single unit, and Figure 29 shows several of them repeated.

Figures 30 through 32 (see page 118) show three more figures woven from the same warp and weft pattern as Figure 29. I've included the drafts here so you can confirm that only the tie-up has changed.

I'll wrap up these examples with some nicely complex pieces of fabric. Figure 33 is a tablecloth pattern I designed. Using the same colors, Figure 34 shows a single unit of the lover's knot pattern. Figure 35 shows that pattern repeated several times to make a piece of fabric.
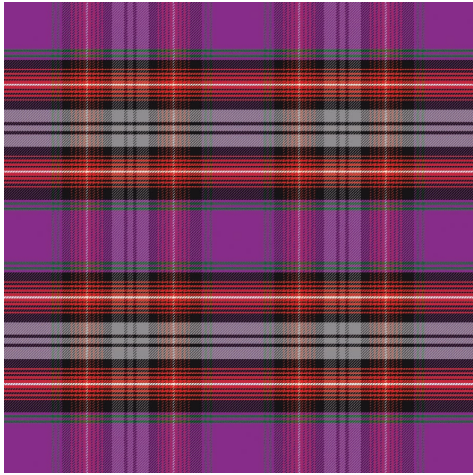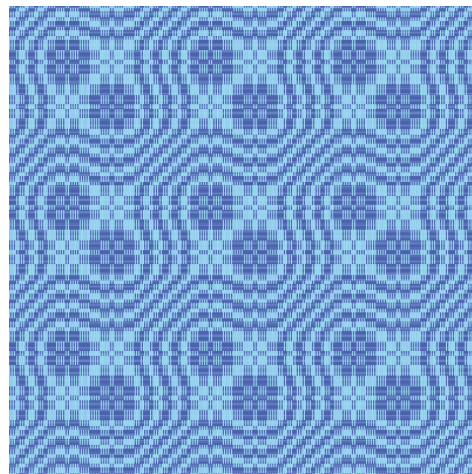
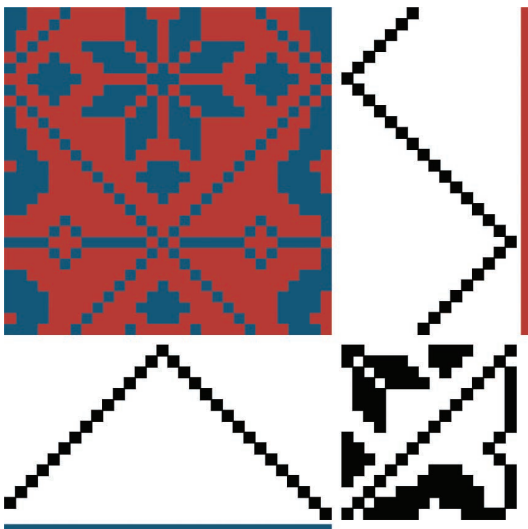**24** A colorful plaid based on the Arran tartan (adapted from draft TS204 at http://www.scottish-tartans-society.org).

25 An original plaid.
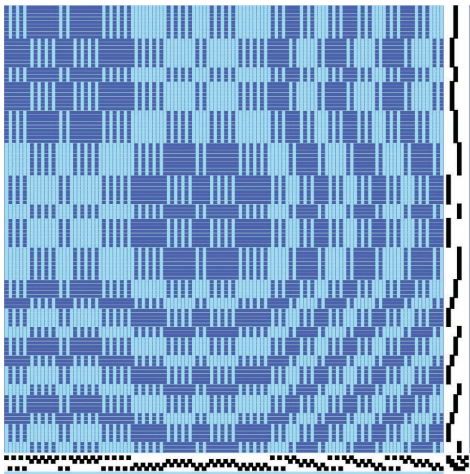
26 A single unit of a cat's-paw design (this draft is from *The Key to Weaving*, pp. 253-255).

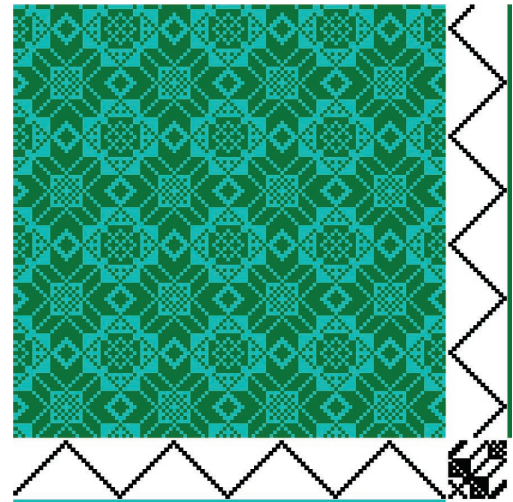**27** Many copies of Figure 26 make a pattern known as a snail's trail.

28 A single unit of a draft (I adapted this draft from *16 Harness Patterns*, http://www.wyellowstone.com/users/ww/annetwil.htm).

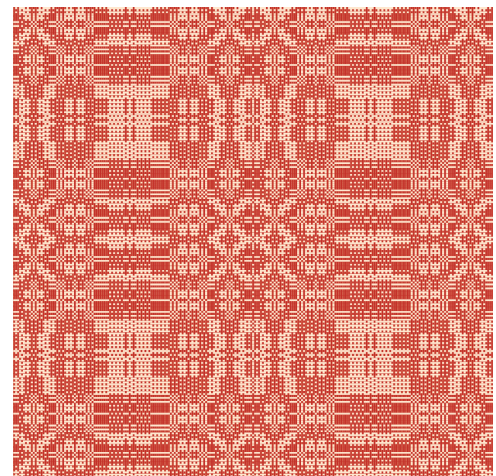**29** Many copies of Figure 28 woven together.

30 A minor change to the tie-up of Figure 28.

**31** A bold geometric pattern (draft adapted from *16 Harness Patterns,* http://www.wyellowstone.com/users/ww/annetwil.htm).

32 Sunflowers on a grassy field (draft adapted from *16 Harness Patterns,* http://www. wyellowstone. com/users/ww/ annetwil.htm).
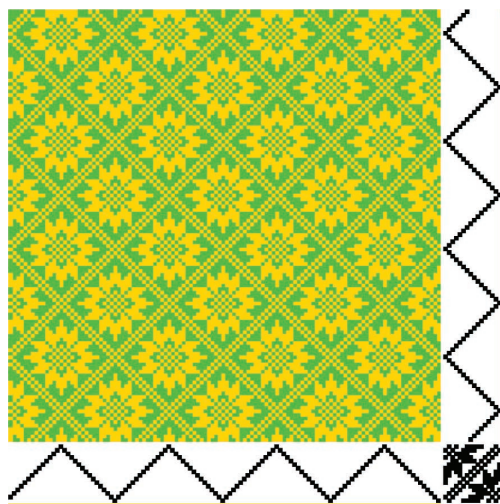
33 An original tablecloth design in red and coral.

34 A single unit of the "Lover's Knot" pattern (the draft is from *The Key to Weaving,* pp. 253-255).
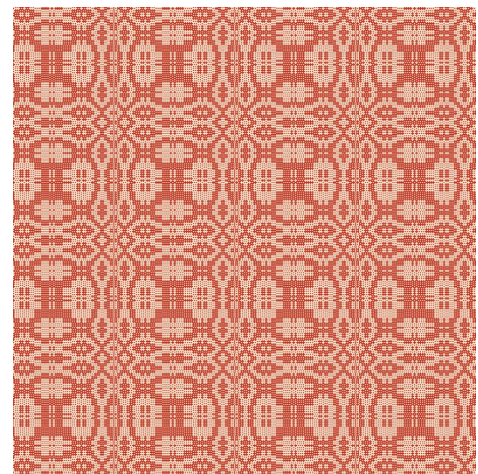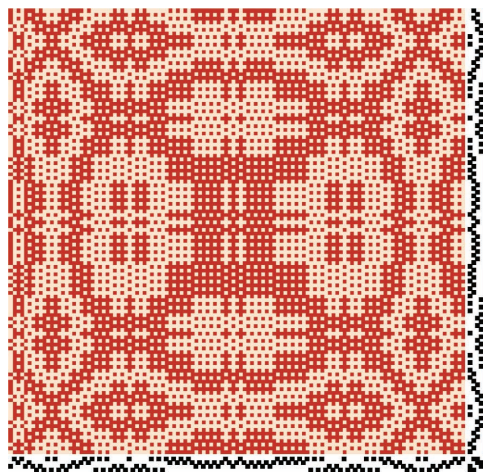
35 A larger fabric woven from Figure 34.

Next time

Now that we've got the basics under our belt, we can think about deducing the draft from a piece of cloth, and writing a program to help us weave on the computer. We'll look at those ideas next time. We'll also look at the weaving language that ships as part of Painter, and extend it in some interesting ways. ■

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