# Interpreting Canvas Weave Matches

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**Abstract**

Automatic methods of calculating canvas thread counts from x-rays of paintings reveal a systematic pattern for warp and weft thread densities that persists along the respective thread directions. These patterns can be used to find paintings that have matching weave patterns, with warp-thread pattern matches more prevalent than weft-thread matches when trying to associate paintings to the same canvas. Exploring the commercial priming process provides a way to interpret canvas matches found from thread counting: when can two paintings that express weave matches be declared to come from the same roll? In addition, the automatic technique must take into account the variations in thread angles to extract the thread count. The resulting angle maps readily indicate the presence of weak and strong cusping. The weft-thread angle map in particular provides additional insights into the canvas weaving process and can be used to elaborate weave matches.

## Introduction

The recent introduction of computer-assisted and computer-automated thread count algorithms has not only greatly eased the tedium of measuring the vertical- and horizontal-thread densities from x-rays, but also provided more information about how thread densities vary across a painting [1]. The algorithms not only measure thread densities across an x-ray, but also thread angles: the departures of the horizontal and vertical threads from coordinate axes. These angle measurements provide immediate information about the presence and degree of cusping.

Thread densities are depicted as *weave maps* that use colors to illustrate how the thread densities vary across a painting (Figure 1). These maps reveal that thread density variations can typify the painting's canvas support. For example, a canvas's horizontal thread counts persist across the width of the painting, but vary vertically in a seemingly random fashion. The vertical threads show a similar variation, but with persistent vertical counts that vary horizontally. In other words, thread packing varies across the painting's support. These variations in canvas thread densities are not specific to each painting, but characterize the larger canvas from which the painting's support was cut. Consequently, thread density variations serve as a fingerprint for the canvas, allowing painting weave maps to be compared in a search for matching weave patterns. We have also found that thread angle maps, as shown in Figure 1, help in determining painting position and, surprisingly, reveal aspects of the canvas weaving process. These interpretations result from understanding the commercial priming process: how canvas is delivered, how canvas rolls are cut from a longer length of canvas—known as a *bolt* of canvas—and then mounted on a priming frame, and how the primed canvas is stored and delivered to retail outlets.

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This paper details how weave matches are determined and illustrates how matching canvas support information can be used in art history. The angle maps and a knowledge commercial priming operations supplement the weave matches, confirming painting support placement (for example, does cusping along a painting's edge confirm placing the support along an edge of a commercially primed strip of canvas?).

We focus on the paintings of Vincent van Gogh for several reasons. First of all, a large fraction of his oeuvre is concentrated in a few museums. But more important are the detailed insights into his painting practices provided by his copious and well-preserved correspondence with his brother Theo, a Paris art dealer, and several artist friends. Not only do the letters describe (in varying amounts of detail) what paintings were executed when, but also when he asked his brother for a new canvas roll and when shipments were received. Furthermore, the letters reveal that, particularly in his later periods, he was very specific about the kind of canvas he wanted.[1] On the one hand, we discovered that his preferred grade of canvas can be easily counted from x-rays, allowing accurate count estimates. On the other, this specificity could complicate the ability to localize weave-matched paintings to a specific roll. Could matching paintings come not from the same roll, but instead from different rolls cut from the same bolt?

[1] Van Gogh preferred 5 or 10 m rolls of "ordinaire"-grade canvas obtained from the Paris colorman Tasset et L'Hôte.

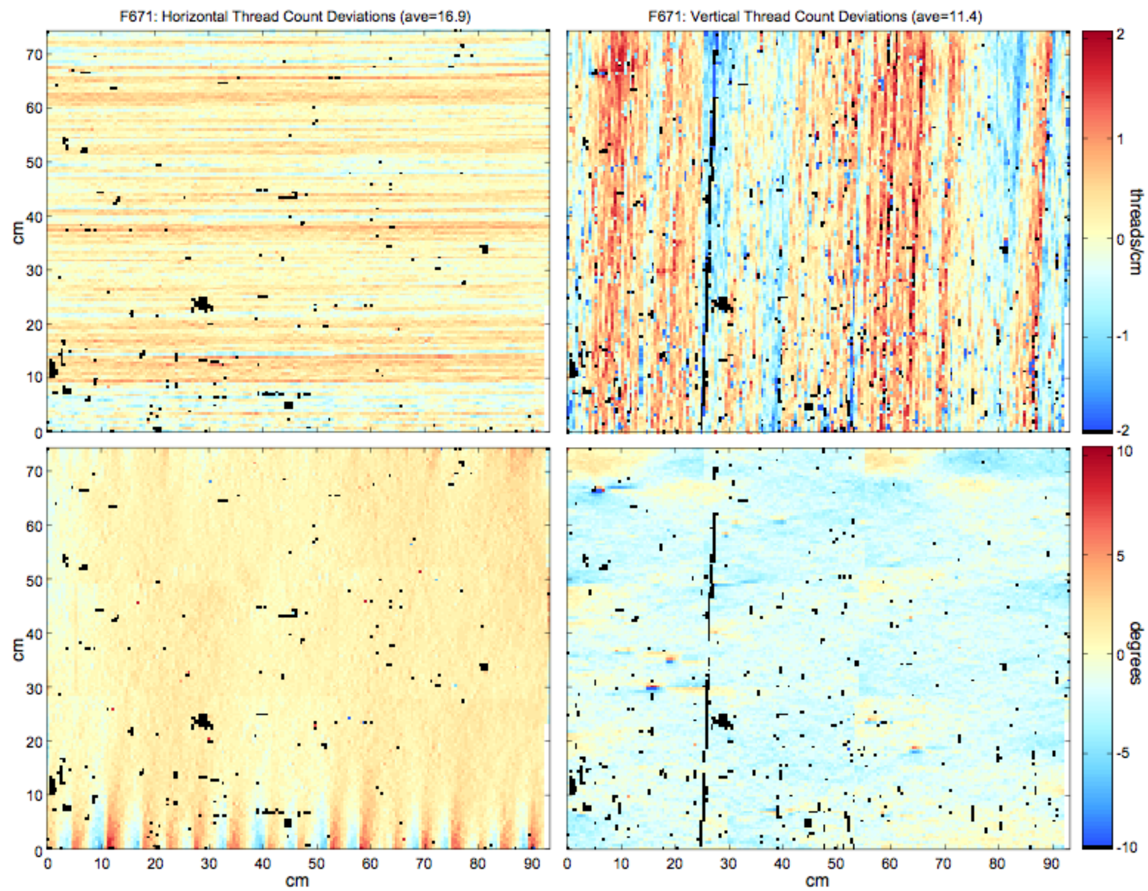


**Figure 1.** Example of weave maps (top row) and angle maps (bottom row) for the van Gogh painting *Blossoming Almond Tree* catalogued [2] as F671. The colorbars are the right show how to convert colors into measured thread counts (as differences from painting average) and angles. For F671, the average horizontal thread count is 16.9 threads/cm and the vertical average is 11.4 threads/cm. Black indicates where no measurement was made because the algorithm could not extract a count due to poor legibility of the canvas weave in the x-ray. The warp direction corresponds to the horizontal threads and the horizontal thread angle map shows strong cusping along the bottom of the painting.

## Interpreting Weave and Angle Maps

Thread count (density) measurements are made with the algorithm described elsewhere [1]. The weave maps shown in Figure 1 represent the thread count measured every 0.5 cm for the surrounding 1 cm square as a color, which allows a ready visual representation of thread count variations across a painting. The horizontal- and vertical-thread weave maps look very different. The horizontal-thread densities (counts) vary less (have a more consistent color), have a more persistent count along the thread direction, and vary more rapidly vertically than the corresponding features in the vertical-thread weave map. From many other examples, these features typify how weave maps allow quick determination of warp/weft direction: the horizontal threads in F671 correspond to the warp direction.[2] Because warp and weft threads are handled differently in the weaving process, they have different thread count characteristics. van de Wetering [3] noted that, for hand-woven seventeenth century canvasses, warp threads tend to vary less than weft threads.[3] We have found this criterion to be reliable in 80-90% of the paintings we have examined. By exploiting the features just described, we believe that weave maps can provide additional criteria that will improve warp/weft judgment.

Angle maps provide different information. If the canvas weave were perfect, with the horizontal and vertical threads crossing each other at right angles, the measured thread angles should be zero, which corresponds to a light golden color. The horizontal-thread angle map shows such consistency except near the bottom of the painting, where the color variation suggests the horizontal threads are waving up and down slightly. Such variations indicate cusping, in this case strong cusping. Because cusping occurs only along one side of the painting (none along the top and the vertical-thread angle map shows no cusping), the canvas support must have been primed not on the painting's strainer, but on a larger priming frame. If there had been cusping on four sides, then the interpretation would be that the ground was laid on unprimed canvas after it had been tacked to the strainer.

The vertical-thread angle map shows additional features. First of all, across the top of the painting, subtle hints of angle variation can be seen as gold and dark blue "clouds" that systematically appear. Secondly, isolated sharp color changes can be seen (three appear on the left side of the vertical thread angle map). Note that at least in this example, these features occur only in the weft-thread angle map. We have found this to be the case in all of van Gogh's paintings, as well in the case of other artist's works.

## Weave Matching Procedure

The first step in the weave matching procedure is to determine whether the thread-count histograms agree sufficiently. We find the best agreement between the two pairs of measured thread counts (does the horizontal and vertical thread count from one painting agree most with horizontal and vertical from another painting or with vertical and horizontal?) and use a detection-theoretic technique to determine the degree of agreement [4]. Only if the histograms agree sufficiently—what we call a *count match*—do we consider determining if the two x-rays have a weave match.[4]

Once a count match has been found, we calculate deviation maps for a painting's x-rays and determine warp/weft directions. We then collapse the deviation maps along their count-persistent directions (horizontal direction for horizontal threads, vertical for vertical threads) to obtain what we term a *profile* that summarizes thread count variations. We then correlate the pairs of profiles to determine if they sufficiently agree to declare a match. In more detail, we take the vertical and horizontal profiles from two x-rays. We first correlate vertical-with-vertical, horizontal-with-horizontal, and retain the pairing that

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[2] By convention, the threads along the long direction of a canvas roll are the warp threads and the short-direction threads running across a roll the weft threads.

[3] Our thread count measurements confirmed this observation for late nineteenth century artists' canvas.

[4] We must make sure that the x-ray-wide thread counts agree sufficiently because two deviation maps could agree even though the average thread count subtracted from the weave maps to produce them do not agree. In fact, we have found that such false agreements do occur.

yields the largest correlation [4]. Just relying on this comparison does not take into account the various possibilities for how a canvas section cut from a larger sheet could have been oriented: it could be rotated arbitrarily and, if not pre-primed, flipped over. Letting $v_i$ denote the vertical profile for painting $i$, $h_i$ its horizontal profile, and rev(•) the operation of reversing a profile, the largest of the following eight pairs is selected to represent a possible weave match: $v_1 \longleftrightarrow v_2$, $h_1 \longleftrightarrow h_2$, $v_1 \longleftrightarrow h_2$, $h_1 \longleftrightarrow v_2$, $v_1 \longleftrightarrow \mathrm{rev}(v_2)$, $h_1 \longleftrightarrow \mathrm{rev}(h_2)$, $v_1 \longleftrightarrow \mathrm{rev}(h_2)$, $h_1 \longleftrightarrow \mathrm{rev}(v_2)$. The degree of correlation of the maximal pair must exceed a threshold to declare a calculated weave match. Because warp and weft threads have different characteristics, the threshold for weft matches is lower than for warp matches.

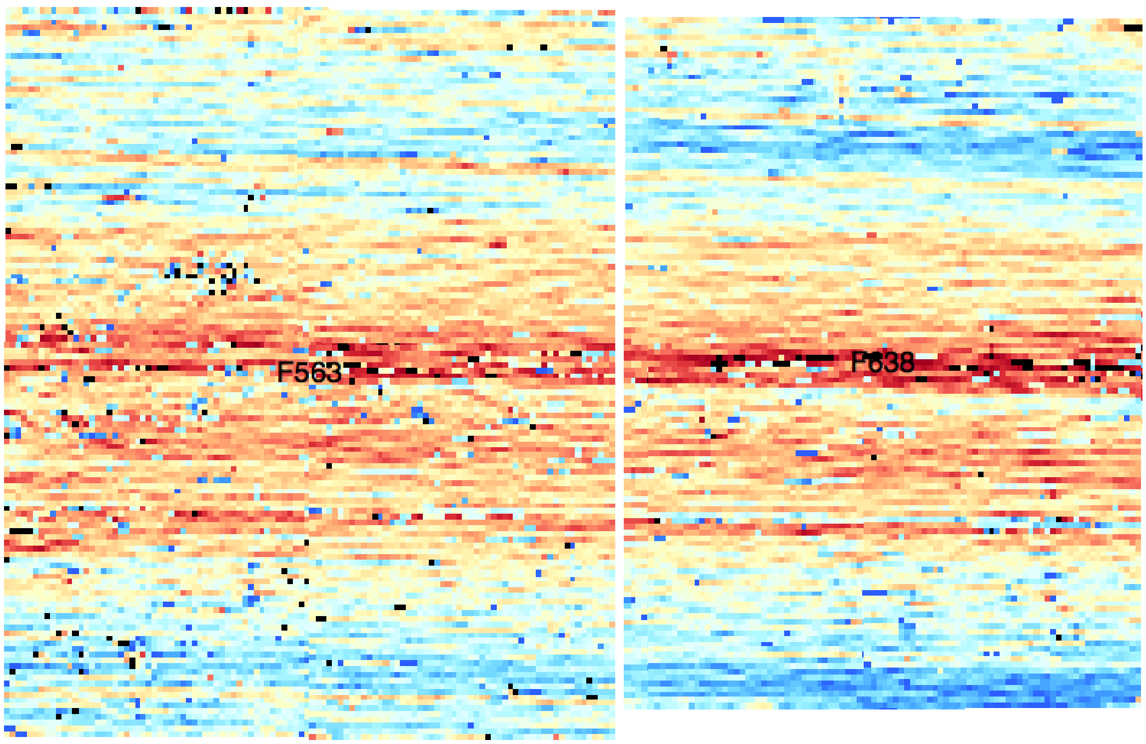


**Figure 2.** Example of a weft-thread weave match between *Haystacks under a Rainy Sky* (F563) and *Two Poplars on a Road Through the Hills* (F638).

Once the x-rays for two paintings are calculated to have a weave match, we have found we must observe the match by constructing deviation maps for the entire paintings and comparing them in the suggested alignment. Warp thread matches suggested by single-x-ray calculations usually survive full-painting evaluation, but not weft matches. The wide-stripe characteristic of weft threads can produce a calculated match just because two wide stripes happen to match. Such potential matches may not persist across a larger segment of canvas, which can easily span more than one x-ray. In such cases, the matches are discarded. Figure 2 shows a typical weft-thread weave match; warp matches are shown in Figure 3. In several cases, warp-thread weave matches allowed us to align several paintings that do not all match each other. This can occur, for example if painting 1 matches painting 2 and painting 2 matches painting 3 but painting 1 and painting 3 do not because they do not overlap in either warp or weft. In this case, the second painting straddles the other two and brings the paintings together. We term the paintings that share a weave match in this way a *match clique*. The weave and angle maps for a clique are shown in Figures 3–6.

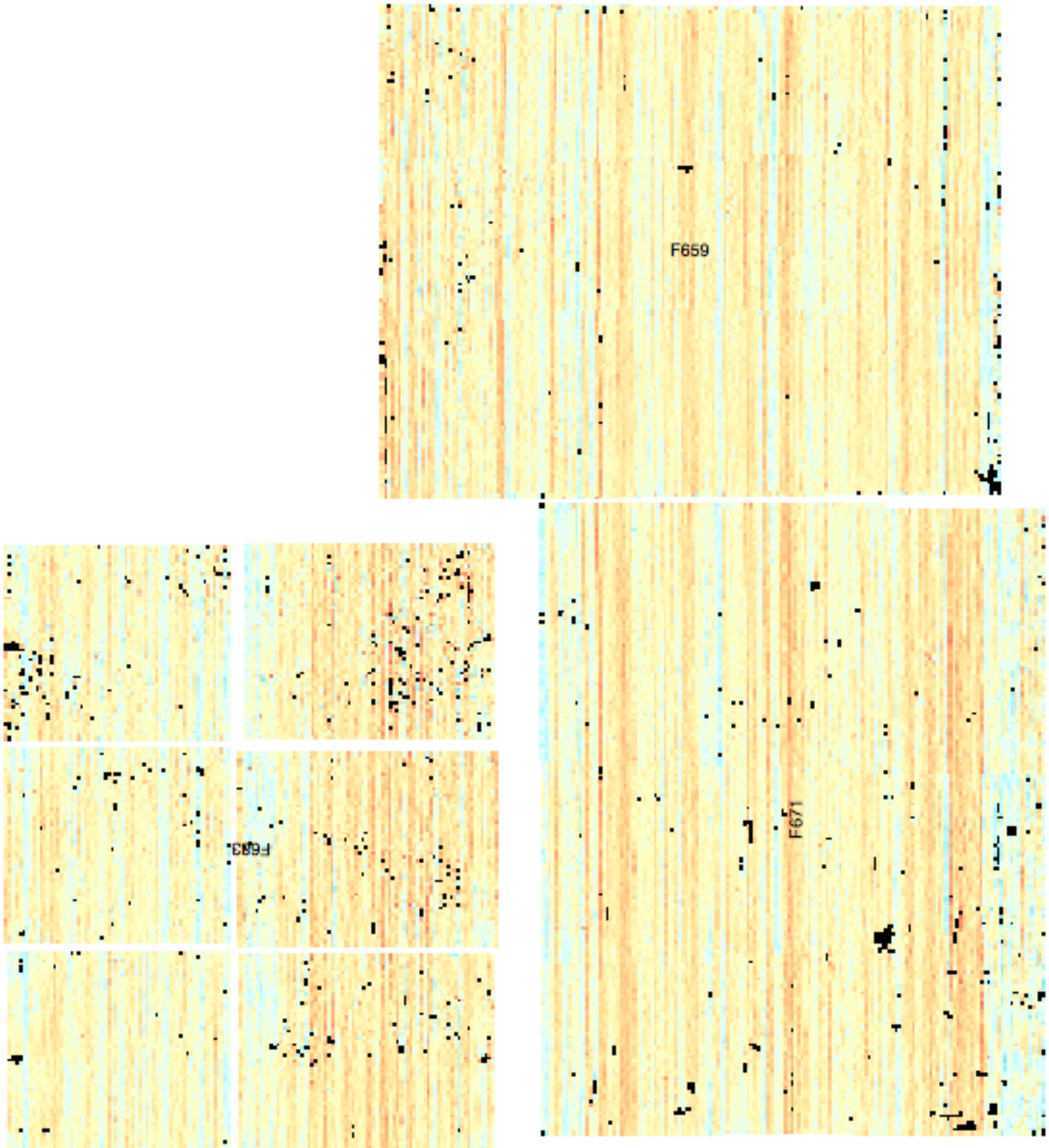


**Figure 3.** Aligned warp-thread weave maps for three of Vincent van Gogh's paintings F659 (*The Garden of Saint-Paul Hospital*), F671 and F683 (*Road with Cypress and Star*). The convention in this and subsequent aligned weave maps has warp threads oriented vertically, weft threads horizontally. To depict weave matches, paintings may need to be rotated to conform to this convention. The catalog labels on the weave maps indicates the "up" direction for the painting.

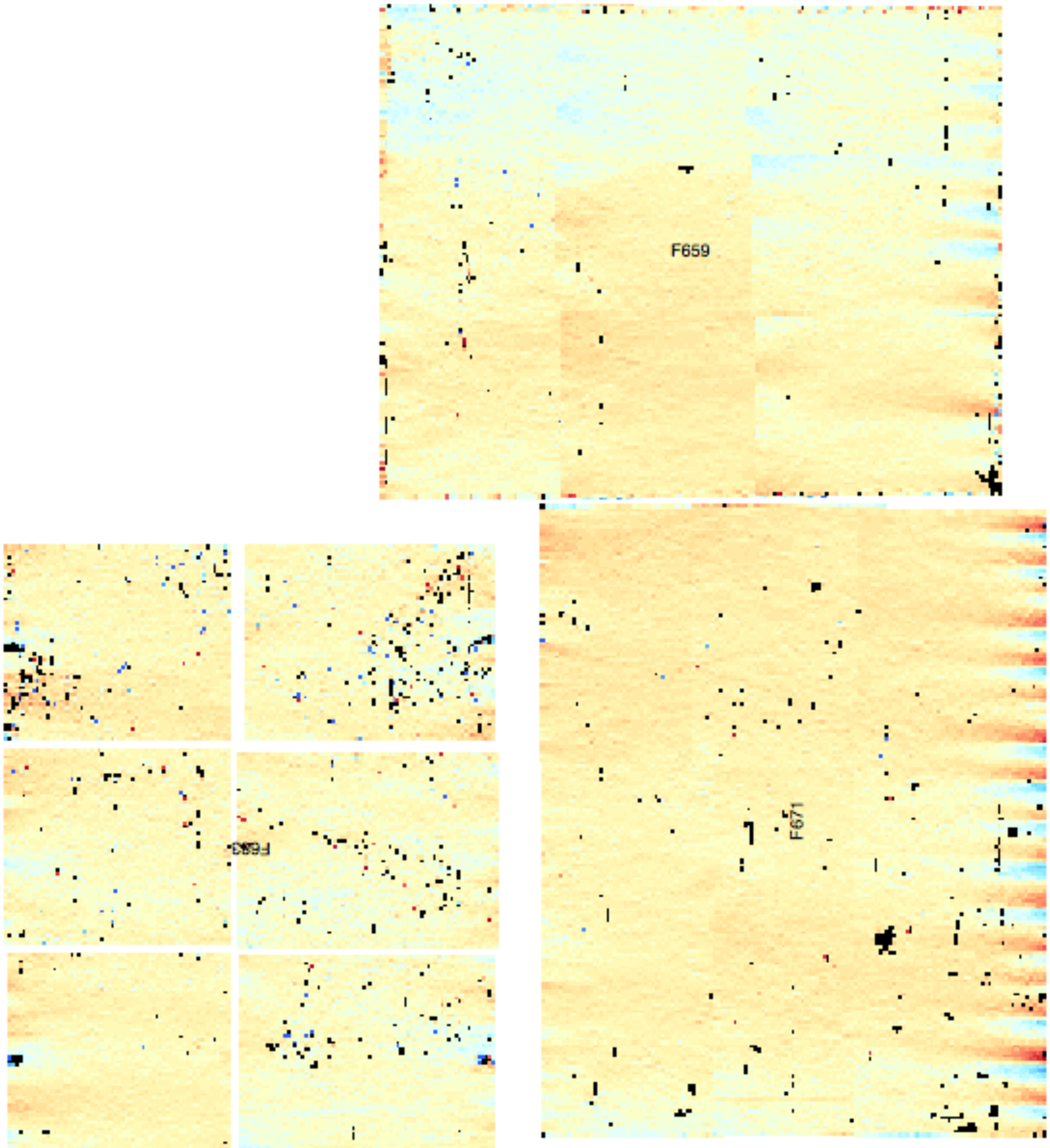


**Figure 4.** Warp-thread angle maps for the alignment shown in Figure 3. The neutral gold color indicates an angle of about zero. The color variations along the right side of F671's warp angle map indicates primary cusping. Hints of strong cusping are present in F659's map.

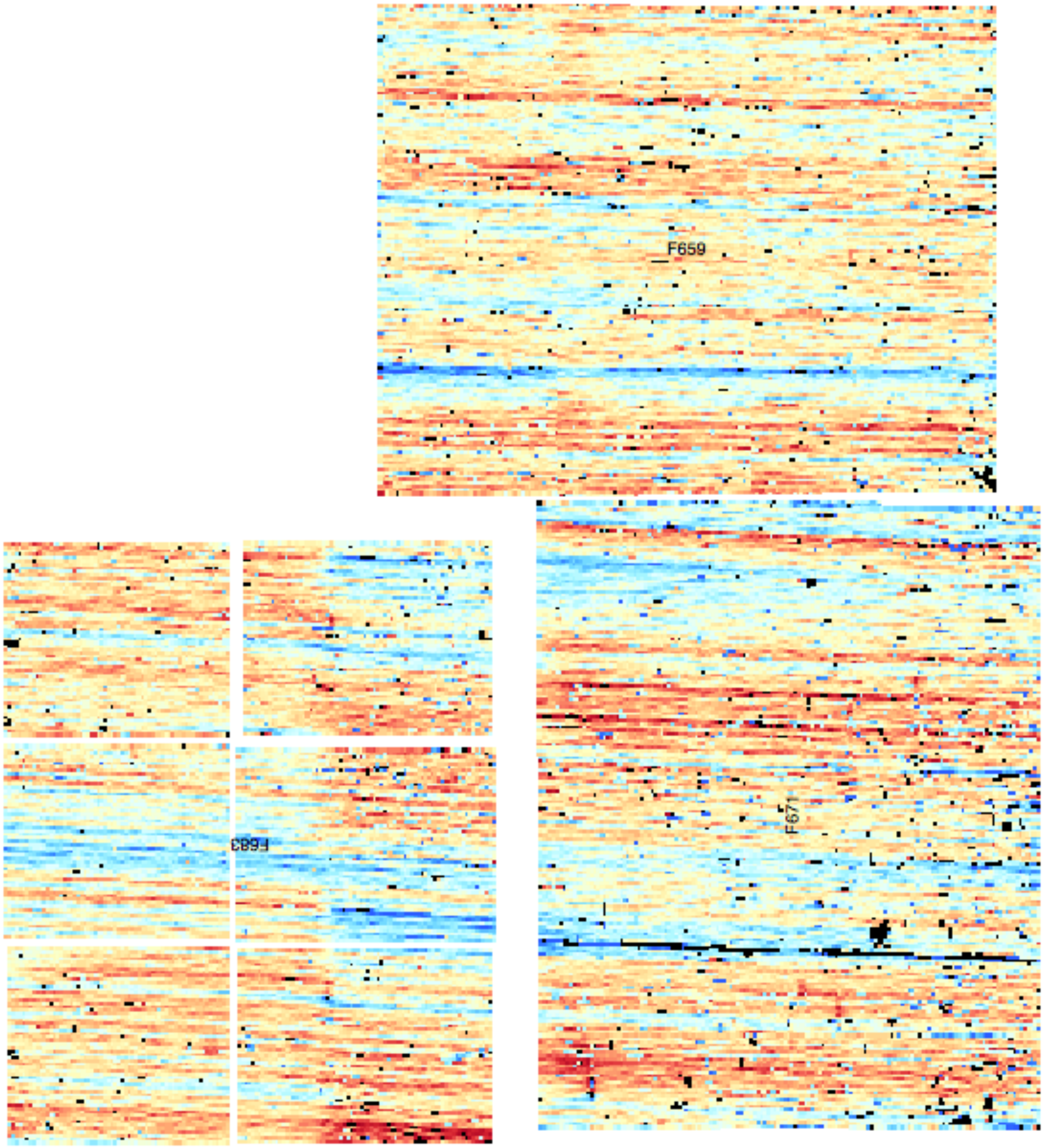


**Figure 5.** Weft-thread weave maps for the aligned paintings shown in Figure 3. Here, F671 and F683 show strong indications of a weft-thread weave pattern match.

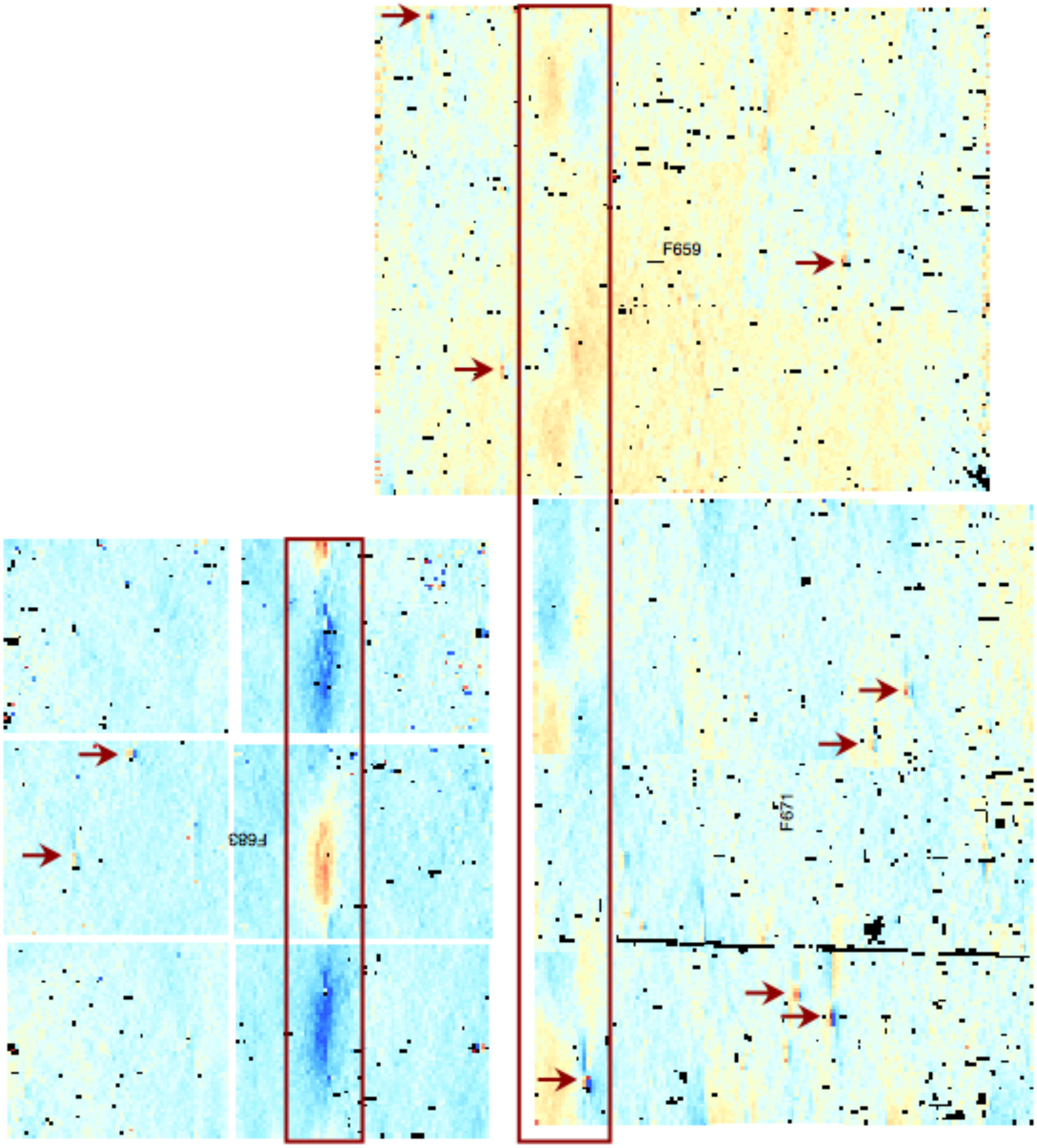


**Figure 6.** Weft-thread angle maps for the warp- and weft-aligned paintings shown in Figure 3 and Figure 5 respectively. The arrows indicate locations showing an abrupt change of weft-thread angle. The left box highlights a series of departures of the weft threads from horizontal. The right box indicates a more subtle change of angle having both a different appearance (two horizontal changes of color that alternate vertically) and a wider separation than that shown in the left box.

## Interpreting Weave Matches

The reason to determine weave matches is to locate the relative positions of two paintings on a canvas sheet. Once a warp- or weft-thread weave match is found, the two paintings are aligned in one direction but the distance between them in the opposite direction cannot be determined. For example, if the warp-thread deviation patterns match (as in Figure 3), their lateral alignment is known, but they could be close together or far apart in the warp direction. The opposite holds true for weft matches, but these are far more constraining because canvases are narrower in the weft direction.

The location of warp-thread matches in the weft direction on the canvas sheet can be further detailed by considering the angle maps. Angle maps reveal the presence of cusping in a painting. Strong, so-called primary cusping occurs when the canvas sheet is stretched, sized and primed; the sizing and primer (ground) seal the thread deviations that occur at the fixture points on the priming frame. If primary cusping occurs on all four sides of a painting, the canvas was first cut to size and stretched on the working-size frame before it was prepared for the artist's use. In this case, preparatory size and ground layers only cover to the front edges of the picture area, but do not extend onto the tacking margins that were folded over the sides of the stretching frame. If primary cusping occurs on one side, two opposite sides, or not at all, the painting's support was primed on a larger priming frame and the support cut from the larger primed canvas. In this case the preparatory size and ground layers coat the tacking margins of the picture support too. If a painting's angle map reveals primary cusping on one or two opposite sides, that painting's support was cut from the edge(s) of the sheet and a painting that weave matches in that direction should also show cusping. The absence of primary cusping implies the support did not from the sides of the sheet.

van Gogh repeatedly requested ten, occasionally five, meters of canvas, corresponding to the length (warp direction) of a commercially primed roll that usually measured about 2.10 m wide (weft).[5] Exploring the practices of such firms reveals that canvas rolls were cut from a much longer sheet we term a *bolt*.[6] Common practice in manufacturing artist-grade canvas was to produce 100 m or 200 m long bolts, which were shipped to a commercial priming company. An important detail is that a bolt was shipped as an accordion-style stack, probably because a stack can be more efficiently shipped than a large roll. The company would cut these bolts to length, a little more than 10m long, and prime each separately.

What follows is a description of one company's sizing and priming procedure that fits with our findings on van Gogh's works, though other methods for preparing artist canvas probably existed. A priming frame is depicted in Figure 7. The short ends of the cloth were folded and nailed to upright bars. One bar was affixed to the end of the priming frame and then the other bar attached to the other end of the frame, stretching the canvas taut in the process. The top of the canvas was then pushed onto a set of spikes protruding from the frame. A set of hooks inserted through the canvas's bottom edge and then laced with a length of rope to the frame that stretches the canvas vertically. The nail/hook system stretches the canvas in the weft direction, which has the effect of creating cusping in the warp threads (see Figure 4). The intervals between the fixed spikes at the top were typically shorter and more consistent than that between the hooks inserted each time by hand along the bottom. Consequently, cusping should differ along these edges.[7]

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[5] For example, see letters 800, 801, 808, 810, 823 and 829 from July 14/15, 1889 to December 19, 1889 [5].

[6] The authors are indebted to Philippe Huyvaert, President of nv Claessens sa, for devoting his time for a tour of his operations and answering our questions about his manufacturing practices. The company is exceptional for its knowledge and skills concerning traditional hand methods of preparing artist canvas, which it still practices there today.

[7] These findings agree with what we see in the angle maps of van Gogh's paintings on Tasset et L'Hôte canvas, suggesting that the canvas was indeed stretched in a manner

Furthermore, since the hooks were placed by hand, the spacing could be more irregular along the bottom edge. Because the canvas ends are nailed to the *sides* of the end bars and the primer does not extend to the tack locations, one should not expect cusping in the weft direction.[8] After the primer has been applied and has dried, the canvas is removed from the frame and rolled onto a rod for shipping to the client. If the firm had a good customer that repeatedly asked for rolls of the same grade of primed canvas, it would hold them in reserve, shipping them upon request.

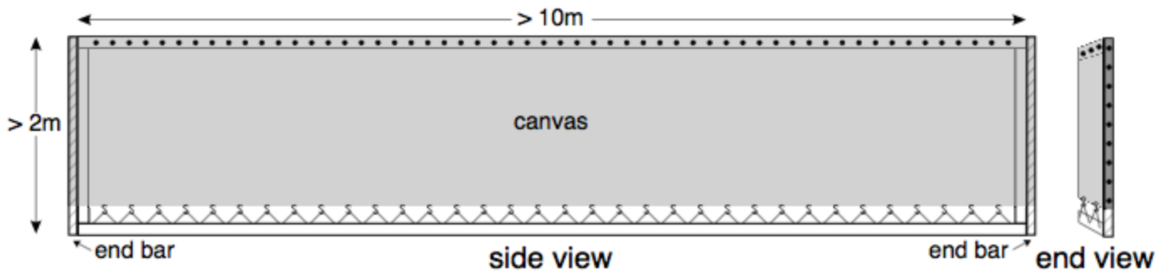


**Figure 7.** Schematic representation of a commercial priming frame. The black dots represent spikes. Note that the bottom edge is stretched with a hook-and-lace mechanism.

## Weft-Thread Weave and Angle Maps

Warp matches dominate the weave matches we have found for reasons described previously and warp-thread angle maps provide crucial cusping information. We have found that in such cases, the weft-thread weave and angle maps can provide interesting supplemental information. Figure 5 shows the weft-thread weave maps for the paintings warp-aligned paintings shown in Figure 3. Note that the map for F683 shows a pronounced change about a third of the way in from the right. The associated angle map (Figure 6) shows that the thread angles as well as densities change dramatically along a vertical (warp direction) axis (see the left red box). Examining the x-ray (Figure 8) reveals a large warp thread that separates different weft-thread densities and angles. This feature occurs in the weaving process and indicates that the loom used to produce this canvas was of a particular design: a half-width loom in which weft threads must run over a sharp U-shaped track [7].[9] Consequently, this feature must run down the center of a roll/bolt. Furthermore, the change in weft-thread weave pattern across the middle means it will be difficult to find a weft-thread weave pattern match between paintings having supports cut from the same roll side-by-side but lying on either side of center.

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similar to this hook-and-lace system on an upright priming frame and them primed. An alternative commercial practice was to simply nail the four canvas edges at consistent intervals to the sides of a priming frame that had been laid flat on trestles for applying sizing and ground layers. This procedure is used today by the French Company Lefranc Bourgeios [6].

[8] We have found strong weft-thread cusping for two paintings that aligned in weft. Cusping strength, as measured by the size of the thread angle deviation, was much larger than the warp thread cusping introduced by the priming frame. Philippe Huyvaert informed us that cusping occurs in the canvas weaving process due to the initial slackness in the tension of the wound bobbin. Its presence indicates the beginning of a bolt.

[9] We are indebted to Philippe Huyvaert, President of nv Claessens sa, for this insight.

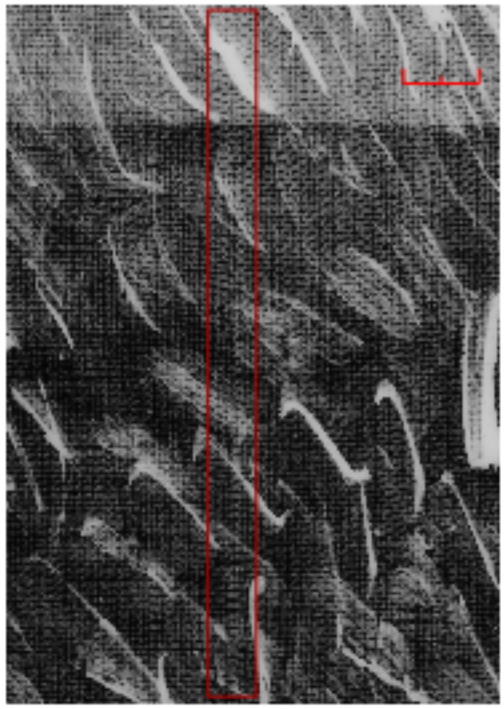

**Figure 8.** A detailed view of a portion of an x-ray taken from F683 shows a warp-thread "seam" running down the center (enclosed by the rectangle), with a large change in the angle of the horizontal (weft) threads on either side. The width of the red scale corresponds to 1 cm.

Also seen in the weft-thread angle map are isolated red-blue regions (indicated by red arrows in Figure 6). These seem to occur randomly and not align with each other as does the half-width loom feature. Examining a x-ray in one of these locations (Figure 9) reveals a rapid change in the weft threads, as if they were being gathered together and pulled vertically. Again, Mr. Huyvaert said that this indicated the presence of a warp thread repair, performed during the canvas weaving process as a part of quality control. A new warp thread is woven and then pulled. It is the pulling action that leaves a mark in the weft-thread angle map. Since such repairs occur infrequently, they provide no information for aligning paintings.

Finally, we found cloud-like features in the weft-thread angle map aligned in the warp direction (see the tall red box in Figure 6). This feature occurs in several warp-aligned paintings in one particular clique. Measurement of the spacing between like-colored clouds occurring in the same painting gave a result of 50–55 cm. This result is tantalizingly related to the width of the bolt stack. Mr. Huyvaert speculates that this feature means that the bolt was tied with a rope very tightly, distorting the angle of the weft threads. We have extended the weave match shown in Figure 3 and subsequent figures to the left by finding overlapping warp-thread weave matches that spanned the width of a canvas roll (a little over 2 m). The cloud feature does not occur on the left side of this match, and we have not seen this feature in any other match clique. Consequently, this feature confirms that the paintings were executed on pieces of canvas cut from the same bolt.

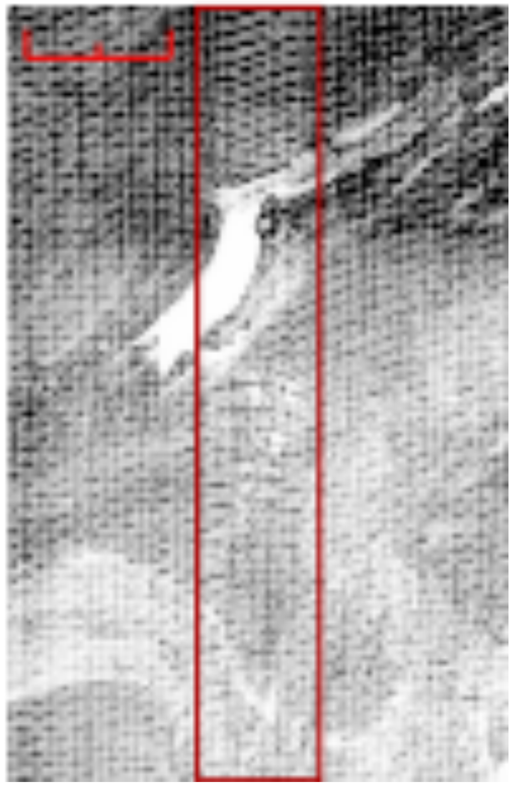

**Figure 9.** Detail of the x-ray for F671 centered at the bottom-left arrow location shown in Figure 6. The rectangle encloses the disruption of weft threads that evidences a warp thread repair. The width of the red scale corresponds to 1 cm.

## Conclusions

The weave pattern introduced by slight manufacturing variations can be used to search for warp- and weft-direction weave matches. In our experience, warp-direction weave matches are very sharp and well-defined; weft-direction matches are generally much more vague and ill-defined.

The angle maps provide additional information crucial for interpreting weave matches. They indicate the presence of cusping, which can provide supportive evidence for how the canvas was stretched when the size and ground were applied. In fact, for commercially primed canvas performed on priming frames, such as shown in Figure 7, primary cusping should only occur in the warp-thread direction. Furthermore, in the case of canvases stretched with the spike-hook-and-lace system, one should expect painting supports cut from the same roll to share a narrow spacing between cusps along one edge (corresponding to the top of the priming frame) and a wider spacing across the other (corresponding to the bottom of the priming frame). Additionally, strong cusping in an angle map can be used to confirm the warp-thread direction.

Weft-direction angle maps frequently reveal manufacturing quirks that can help reconstruct relative painting position. The sharp change in angle in the center of a putative bolt indicates the kind of loom used to weave the canvas. We have found two weave match cliques that contain this feature but that do not weave-match each other. We have another clique that does not express the half-loom feature. We have found other features in weft-thread angle maps that may not help in alignment or placement but do confirm the weft direction of canvases.

For commercially primed canvas from van Gogh's era, when one finds a warp-direction weave match among a set of paintings, the best that can be claimed is a *bolt* match, not necessarily a roll match.[10] Since ten to twenty rolls comprise a bolt, bolt matches by themselves say little about the timing of warp-matched paintings. Other considerations must be brought to bear to assign paintings to the same roll, which would suggest a close temporal relationship.

- Paintings having a weft-thread match must come from the same roll. Unfortunately, it is difficult to find and trust such matches.
- The layer build-up and composition (same pigments, same size range and morphology of pigment particles, same ratio of pigments, same binding medium) of the ground for paintings from the same roll must be the same for commercially primed canvas. Priming firms used a variety of grounds, but only one type was used on a roll. Of course, different rolls could have the same ground, but if warp-matched pre-primed paintings have different grounds, they must have come from different rolls.
- van Gogh's correspondences describing paintings he executed at about the same time can help localize paintings to a roll. However, it is not always possible to identify the pictures mentioned with certainty, as in the case of some of his repetitions or serial versions of the same theme. For example, there are five *La Berceuse* paintings, six *Postman Roulin* paintings, and seven *Sunflower* paintings, all painted during his time in Arles.[11]

We are working to determine other criteria so that paintings can be located on a canvas roll rather than a bolt, which would provide insight into the artist's process.

[10] We do not know if looms produced bolts having similar manufacturing variations in the warp direction.

[11] The *Sunflower* paintings differ sufficiently in composition that determining which one is being referred to in a letter can be at least partially, if not uniquely, determined.

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