Following the Geometrical Design Path from Ely to Jamestown, Virginia

Laurie SMITH

HISTORICBUILDINGGEOMETRY

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FRONT COVER

The Monks' Door at Ely Cathedral with foliage interlace, mythical creatures, kneeling monks holding croziers and precision daisy wheel geometry at the cusps of the tripartite arch

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Foreword

This work was originally one of ten presentations given at the joint Society of Architectural Historians of Great Britain (SAHGB) and Vernacular Architecture Group (VAG) Symposium held at the Artworkers Guild in Queen Square, London on 17 May 2008. In the following year a decision was made to publish the symposium presentations in book form, edited by Peter Guillery and published by Routledge, under the title **Built from Below**: ***British Architecture and the Vernacular*** ~ (ISBN 13: 978-0-415-56532-5 (hbk), ISBN 13: 978-0-415-56533-2 (pbk) and ISBN 13: 978-0-203-84770-1 (ebk). This article was presented as chapter 2.

Because the presentation at the Artworkers Guild was given as a sequence of projected geometrical drawings accompanied by a verbal explanation, going into print was initially difficult. The reality that there was no paper text to send to the editor for consideration meant that it became necessary to write one.

With this latest version, the presentation has metamorphosed again, so that what began as a verbal presentation transcribed into print is now electronic. This electronic version enables the drawings and photographs illustrating the text to be placed closer to the words that describe them and the geometrical drawings, which are the essence of the argument, are shown at a significantly larger scale.

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Introduction

A building's design is the conceptual foundation on which its tangible form, visual appearance, function and subsequent history are all built so it follows logically that we comprehend historic buildings more fully if we understand how they were designed. However, the single greatest obstacle to understanding is that, as people of the 21st century, we no longer speak the design languages of earlier times. This is particularly true of the medieval period because the spatial proportioning inherent in geometrical design is largely absent from the design languages of the present which are, in general, dominated by numerical dimensions. In seeking a deeper understanding of medieval buildings and the mindset of their designers it is an essential first step to relearn the geometrical design language of the period.

This chapter evolves from the tangible presence of geometrical, compass drawn symbols carved into the fabric of Ely Cathedral, most prominently in the tympanum of the Monks' door at the eastern end of the nave's southern aisle. An explanation of the symbol's fundamental properties shows that they have applications in building design. The argument is that these carved geometrical symbols represent the geometries used in the cathedral's design, in the layout of the Monks' door and nave floor in particular, and that their presence is a conscious statement to that effect. Sequential diagrams show how the intrinsic geometrical properties of the symbols can be applied, first to design the door itself and, second, after a review of the cathedral's measured record, in the design of the nave's large scale linear floor proportions including the alternating placement of cylindrical and composite piers in the arcade alignments.

Analysis of the spatial configuration of the Ely nave floor demonstrates that a triplicated linear development based on the Ely geometrical symbol generates the nave's floor geometry. The application of this geometrical design system can be found in other buildings and these are, in chronological order, Prior Crauden's Chapel in Ely, the Barley Barn at Cressing Temple in Essex, 17 Court Street at Nayland in Suffolk and the Governor's House at Jamestown in Virginia. While other examples exist where the symbol is duplicated and, in another case, developed into a five symbol linear floor, the focus of this chapter is on examples that embody the symbol's triplication, enabling a specific design geometry to be followed over time.

In close proximity to Ely cathedral, Prior Crauden's Chapel features an identical linear development to the Ely nave floor, though on a very small scale, in the design of two groups of tiles flanking the image of Adam and Eve, the focal point of the chapel's overall floor tile scheme. The triplicated linear geometries defining the Ely nave arcading and Prior Crauden's chapel floor tiles can also be found in the floor plans of the Barley Barn, built by the Knights Templar at Cressing Temple in Essex, in the floor of 17 Court Street, a pair of diminutive semi-detached medieval

1 2

hall houses in Nayland, Suffolk and in Jamestown, Virginia, where the archaeological footprint of the governor's house was recently recovered. Despite the intervention of the Atlantic, these examples have a regional connection, Ely Cathedral and Prior Crauden's chapel being in modern Cambridgeshire, the Barley Barn and 17 Court Street in adjacent Essex and Suffolk respectively while the Jamestown governor's house was known to have been built by carpenters who sailed to America from the Suffolk area. Apart from Jamestown, the greatest distances between the examples are Ely to Cressing or Nayland, each 40 miles as the crow flies or a two day horse ride away, while Cressing and Nayland are just 15 miles or a day's walk apart. The time scale, from 1135 for the Monks' door to 1610 for the Jamestown governor's house, spans a period of 475 years. The survival of this geometrical design system over such a long period and its application in the design of buildings of significantly different status, function and scale raises serious questions regarding our modern understanding and usage of the word vernacular.

Geometrical symbols at Ely Cathedral

The visual language of Ely Cathedral speaks loudly of compass geometry: semicircular arcade vaults, single semi-circular arc and interlaced semi-circular blind arcading, cylindrical piers, half cylindrical pilasters (on cylindrical and composite piers) and a range of compass drawn geometrical symbols.

There are fifteen examples of stone cut geometrical symbols that can be seen by an observer from the floor of the cathedral while two further examples can be seen at triforium level. The symbols fall into two categories, the vesica piscis in which two circles of identical radius each pass through the axis of the other to form an almond shaped mandorla and the daisy wheel in which six circles of equal radius are drawn around the circumference of a seventh to intersect in the familiar form of a six-petalled radial flower. The triforium examples are of four and five petalled wheels, making seventeen symbols in all.

Entering the cathedral through the western tower entrance the eye is taken immediately by the black and white marble maze that fills the entire tower floor

Ely Cathedral, vesicas and daisy wheels

1 2
Vesicas in the angles of the West Tower and above the Nave's west arch
3
Vesica in the Prior's Door tympanum, encompassing the figure of Christ in Judgement
4 5
The Monks' Door tympanum with two daisy wheels at the cusps in the tripartite arch, and a close-up of the left wheel

3

4 5

and then, as the eye adjusts to the interior, the linear perspective of the nave stretching away, through the light from the crossing's Octagon, into the chancel, on to the altar and, finally, to the east window. Watching visitors entering the cathedral, it is noticeable that though many are intrigued by the maze and some follow its track to the centre, very few look up into the western tower itself. Yet here, in the spandrels of the tower's four high arches, are eight large high relief vesicas, placed so that they touch arc to arc at right angles in the tower's four corners, figure **1**. Entering the nave there are two further vesicas high above in the spandrels of the arch, identical to those of the western tower, like eyes scanning the length of the nave from west to east, figure **2**. There is a further vesica in the tympanum of the Prior's door where, flanked by angels, it acts as a mandorla surrounding the figure of Christ in Judgement, the central focus of the door's elaborate sculptural scheme, figure **3**. This door is in the south aisle of the nave where it once gave access to the now lost cloister, its carving viewed from the cloister side.

The Monks' door, which is also in the south aisle and faces into a small surviving remnant of the cloister, features two daisy wheels, placed at the focal intersections of its tripartite arch, beneath another complex sculptural scheme, figure 4. The precision compass arcs of the wheel's carving are clearly visible in the enlarged photograph, figure 5. In the north-eastern corner of the north aisle a further door gives access to the spiral stair rising to the north aisle roof walk and the Octagon. This door, although much simpler in its sculptural scheme and at a humbler scale, nevertheless also has two daisy wheels carved on cylindrical drums to mark the focal points in the arch profile. Finally, at triforium level, at the entrance to the stained glass museum, there is a door with a single drum showing a four-petalled wheel on one side and five-petalled wheel on the other. The drum from the opposite side of this door arch has been lost.The vesica and daisy wheel symbols that are clearly visible in public areas of the cathedral total seventeen. There may be more and it is open to speculation that, before its collapse in 1322, the central crossing tower may have had a similar geometrical scheme to that of the western tower. The important recognition is that geometrical symbols abound at Ely at a variety of scales and locations and are an emphatic geometrical presence. All are cut in stone, all are clearly integral elements of greater sculptural schemes and, significantly, all arise from compass geometry. In seeking evidence of geometrical design methods at Ely it is therefore sensible to consider compass based systems and to recognise the geometrical function of the symbols.

The primary function of the vesica piscis, figure 6, is to generate perpendiculars. If two circles are drawn on a line so that they intersect, a second line drawn through the intersections will cut the first line at 90°. The daisy wheel, figure 7, embodies two vesicas and, therefore, two parallel perpendiculars. The daisy wheel's first function is as a source of 60° angles, figure 8, that can be bisected to give 30°, 15° and so on while an adjacent 60° and 30° combine to give a right angle. The daisy wheel's second function is as a means of determining triangulation and proportioned areas. Because the wheel is compass drawn to a single radius, it follows that all points at which arcs meet are an identical distance apart. Therefore, if three adjacent points are connected the result is an equilateral triangle. Because the circle's axis occupies a central point the remaining two are inevitably on the circle's circumference. Two of these equilaterals are shown in tone in figure 9 and it is clear that a total of six could be constructed if all points on the circle's circumference were linked to its axis. Connecting every second point around the circle's circumference generates a larger equilateral triangle while connection of the remaining three points gives another in mirror image. The two large equilaterals combine to form the Star of David, figure 10. If all six points on the circle's circumference are connected they combine to form a hexagon, figure 11, and if four of the hexagon's points are connected a rectangle is formed which, in modern parlance, is known as a root 3 rectangle. It is most swiftly and accurately drawn by linking points in a compass drawn daisy wheel and it can be seen that its two long sides bisect the wheel's two inherent vertical vesicas (see figure 7). A further rectangular development of the daisy wheel is drawn through all six points on the circle's circumference, figure 12. This rectangle is exactly twice the area of that drawn between four points on the circle's circumference. With the daisy wheel's linear and proportional potential in mind it is possible to consider its application in the design of the Monks' door.

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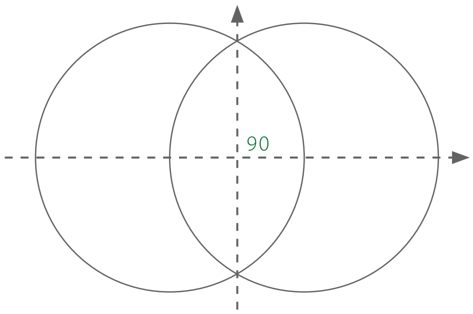

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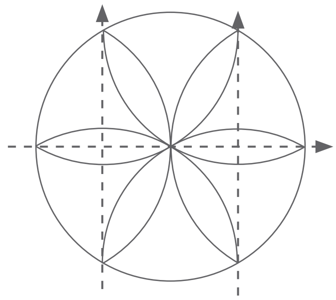

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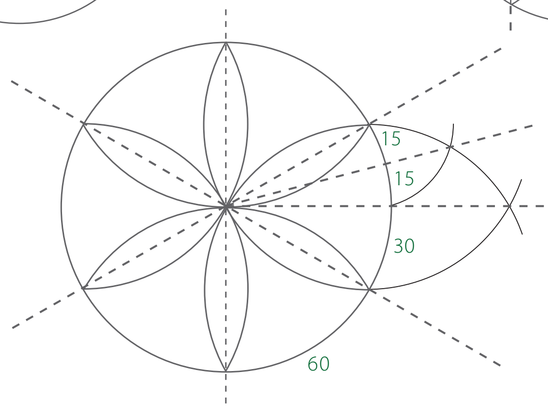
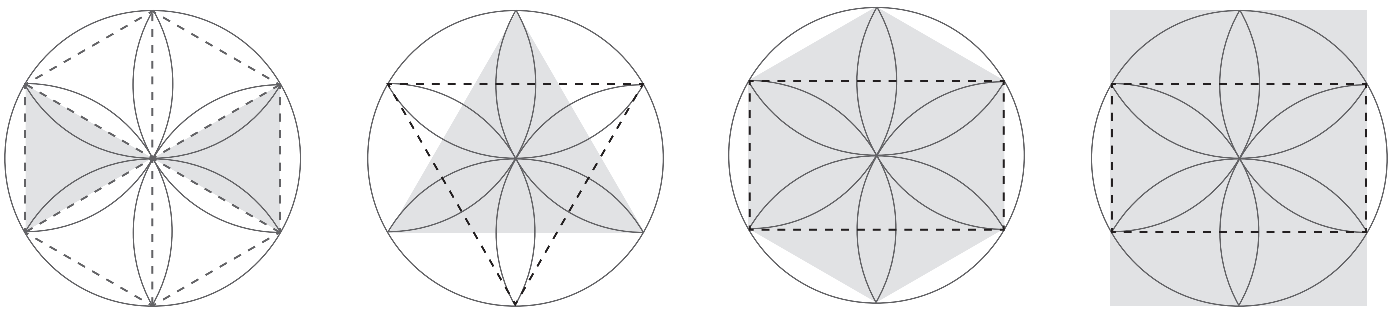




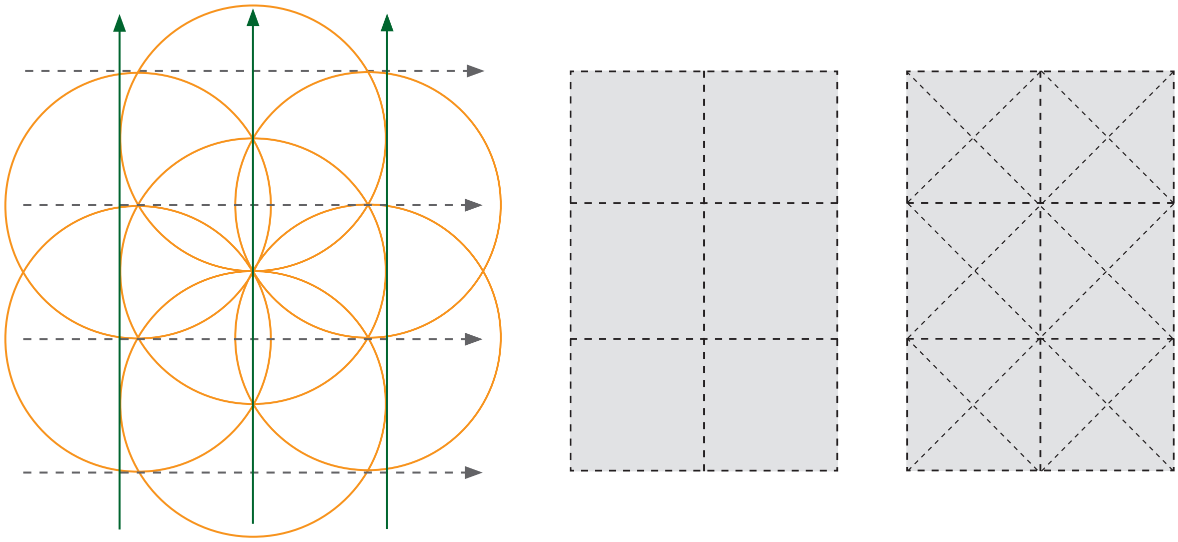
9 10 11 12

Angular and spatial values of the vesica piscis and daisy wheel

Numbers indicate degrees

The Monks' door

The Monk's door[1] is flanked by alternating cylindrical and angular columns rising to capitals though those on the right are obscured by the later masonry of the octagon's buttressing. From the capitals, a semi-circular tympanum arcs above the door. The door itself is without capitals and rises directly into the external arcs of a tripartite arch which, at their meeting with the central arc, features two identical compass drawn modules, see figure 4. These modules, known by modern frame carpenters as daisy wheels from their six identical vesica petals, are cut at the ends of short horizontal drums with chevron pattern around them, like miniature parallels of the cylindrical columns in the nave of Durham Cathedral. The daisy wheel modules are cut from the same stone as a wider decorative scheme that includes two kneeling monks holding crooks, two mythical creatures biting each other's necks, undulating trails of leafy foliage, a precise cylindrical arc of geometrical spirals and, at its apex, a small naturalistic head. All of these are divided along



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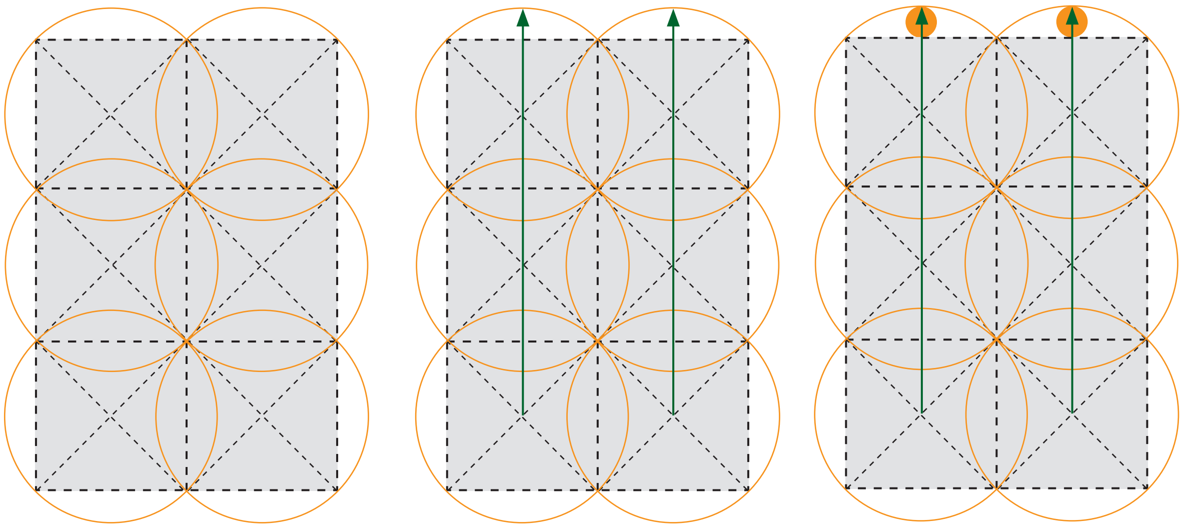
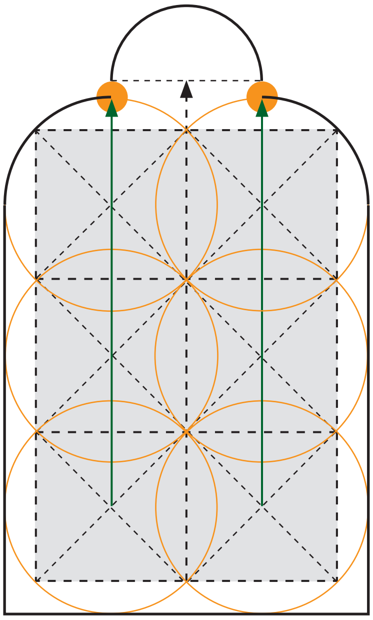


16 17 18 19

their vertical centre line in mirror image. An important recognition is that all four elements, the pure geometry of the daisy wheels, the anthropormorphic figures of the monks, the entwined mythological beasts and the undulating trails of vegetation occupy the tympanum in a unified visual scheme and clearly had equal aesthetic status in the sculptor's mind. The composition juxtaposes the human and spiritual worlds of the kneeling monks, the natural world of interwoven foliage, mythical beasts from the imagination and geometrical precision from the intellect. And it is geometrical precision from the intellect that inescapably occupies the focal points of the door's tripartite arch in the form of two daisy wheels.

Geometrical design is a step by step process where each stage is built logically upon the one before and, as with actual building, some of the stages act solely as scaffolding and are removed after they have served their purpose. The design commences from the full daisy wheel construction of six circles drawn around the circumference of a central, primary circle. Two vertical tangents and a centre line are drawn (in solid line) in the daisy wheel's central vertical row of three circles and four further horizontal lines are drawn (in dashed line) as tangents to the two pairs of horizontal circles, figure 13. The seven lines form a right angled grid



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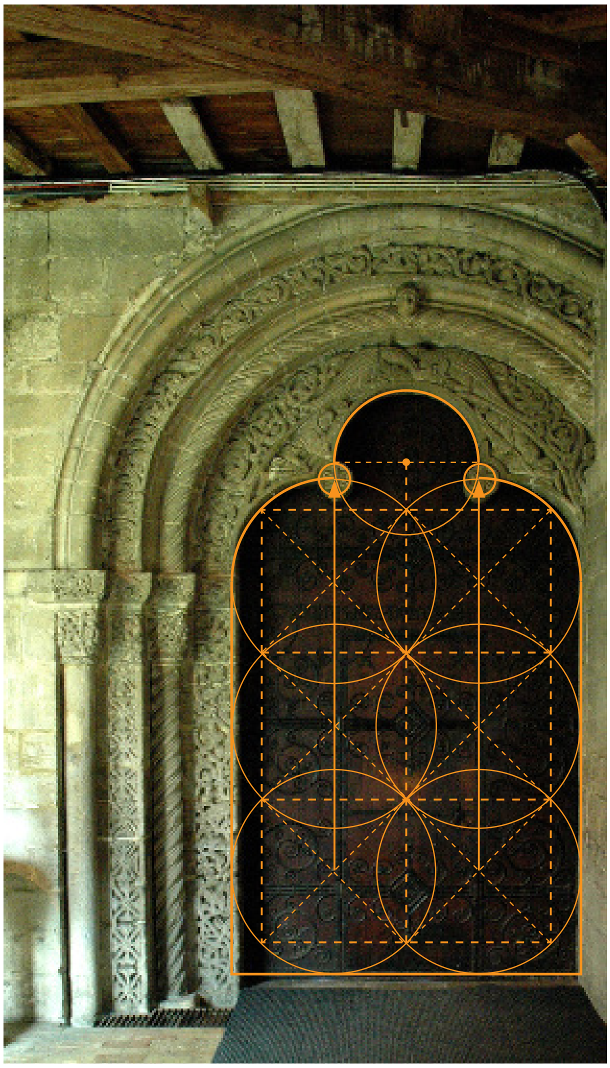


Ely Cathedral, daisy wheels

13 - 19 Geometrical development of the Monks' Door
20 The geometry superimposed on the door

that frames a block of six equal squares, figure 14. Diagonals drawn across all six squares, figure 15, intersect at the axes of six circles drawn to pass through the corners of the squares, figure 16. Vertical lines drawn through the intersections of the diagonals cut the top two circles at their apex, figure 17. Figure 18 shows that two further small circles, shown in amber tone, can be constructed so that their diameters are dimensioned exactly between the top pair of circles and squares. In figure 19 the small amber circles are redrawn with their axes at the upper poles of the top two circles and a horizontal tangent is drawn between their own upper poles. The vertical centre line is extended upwards as far as the tangent and this point is the axis for a semi-circle which has the tangent as its horizontal diameter. Finally, tangents to the six circles combine with the circumferential arcs of the top three circles to give the full profile of the Monks' door. Figure 20 shows the geometrical construction superimposed on a photograph of the door. Significantly, the design process both begins and ends with the daisy wheel, metamorphosing from the initial seven circle construction, through a grammar of tangents, squares and circles, to the dramatic paired daisy wheels in the doorhead, the geometrical cusps that mark the changing curvatures of the tripartite arch.

Previous analyses of the nave floor

There have been a number of theories regarding the nave's layout. W. P. Griffith, writing in 1850 - 52, proposed a system of equilateral triangulation based on the width of the nave (including external walls) so that three triangles connected in line, apex to centre of base, gave the nave's floor[2], figure 21. This was correct in terms of overall proportion but it misses the beat of the nave's internal rhythm including the aisles, arcades and the juxtaposition of cylindrical and composite piers. However, it does suggest the presence of a triplicated proportional unit.

Eric Fernie's analysis of the cathedral's overall dimensions established a range of proportional relationships based on the √2 rectangle, a rectangle that extends a square to the length of its own diagonal[3]. The square's diagonal is in √2 relationship to its sides so that, with a side length of 1 unit, the diagonal's length is 1.4142, the square root of 2. Drawing a square, based on the nave width including both arcades, and developing it as a series of √2 rectangles across either aisle makes the square's diagonals arc onto the outer face of the aisle walls, figure 22. So, although the root 2 rectangle is clearly present, it also fails to mesh with the locations and alternation of cylindrical and composite piers in the nave arcades.

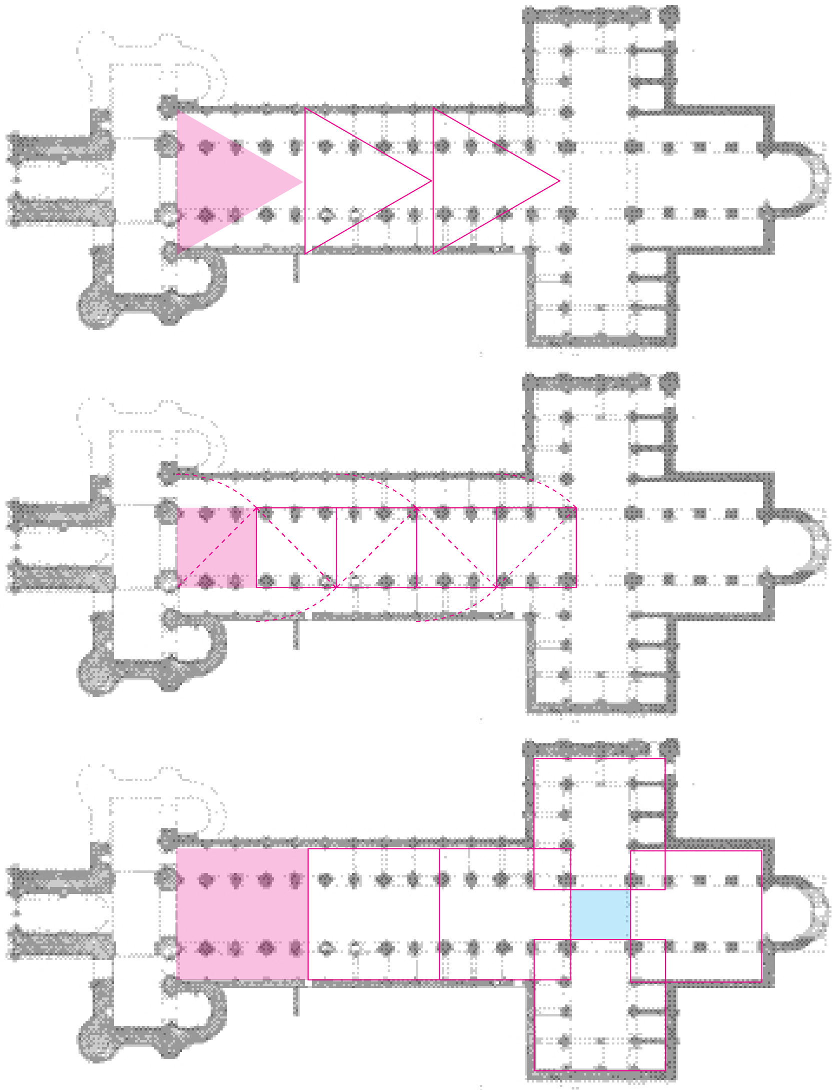
Nicola Coldstream presents a different theory. Quoting Lechler, she shows that a square, based on the internal width of the choir, can be used as a module to generate the major proportional relationships of the cathedral floor. Three identical squares define the choir and transepts while a linear block of three squares defines the nave, figure 23. The choir square, north and south transept squares and the first of the three nave squares overlap each other within an identical square formed by the crossing, but leave a small rectangle, neither square nor √2, remaining undefined at the crossing's centre. The three great nave squares, again suggesting a triple proportional unit, nevertheless fail to define the rythm of the cylindrical and composite piers in the arcades. However, she recognizes the important point that '*while geometrical constructions yield irrational numbers when measured they are easy to construct and are memorable as drawings*[4]'.

In a further theory, John Maddison presents a more practical approach. He considers that plans, drawn on vellum or on plaster walls or floors, using compasses and an L-shaped square, were replicated at large scale using simple peg and cord geometry. This is the first theory to introduce circle geometry at the design stage. In order to attain this, a fundamental unit of proportion was required and for this he returned to Eric Fernie's analysis of the Ely floor which recognised a standard unit of 5½ feet throughout the plan. The unit doubled gives 11 feet and trebled 16½ feet, the medieval Rod. Many of Ely's dimensions accord with this unit so that the nave's wall thickness and foundation depth are both 5½ feet while the maximum exterior width is 88 feet (sixteen units), and its internal width 77 feet (fourteen units), both multiples of 11. The beauty of 11- base numbers as a mnemonic in a pre-numerate society is easy to see ~

11 22 33 44 55 66 77 88 99

Scaling up from inches to feet is also simple. A 5½ inch radius circle on vellum or plaster, doubled, gives an 11 inch diameter which can be stepped out twelve steps along a chalk line to full scale in feet. However, the book has no drawings that demonstrate the peg and cord theory in practice[5].

Fernie produced a measured floor plan of the Norman cathedral and it is this that underpins the geometrical proposals presented in this paper. Referring to the measured drawing and moving from west to east along the nave's aisles, the recorded consecutive bay dimensions in the north aisle are 5.47, 5.11, 5.19, 5.13,



Previous analyses of the Ely nave floor

Top, W P Griffith's triple equilateral triangles
Centre, Eric Fernie's √2 rectangle developments from a series of squares
Bottom, Nicola Coldstream's overlapped squares

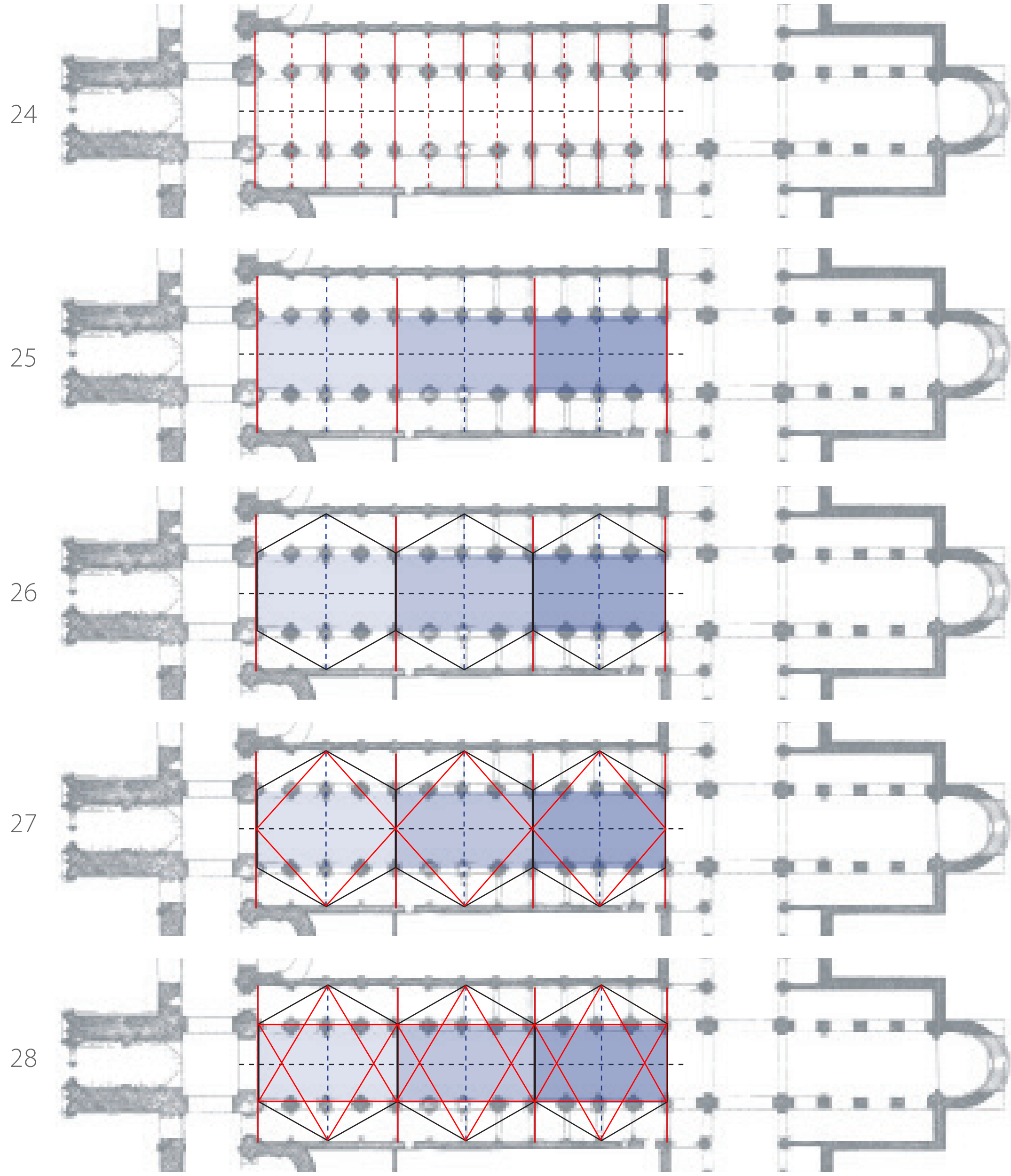
5.22, 5.10, 5.20, 5.08, 5.05, 5.02, 5.08 and 5.05 metres and in the south aisle 5.28, 5.16, 5.18, 5.14, 5.14, 5.16, 5.19, 5.05, 5.1, 5.07, 5.04 and 5.23 metres. The nave's five recorded dimensions from west to east between the arcades are 10.08, 10.10, 10.06, 10.12 and 10.14 metres, showing that the floor narrows at the nave's centre and widens at either end with its the greatest width at the crossing. The full nave width including the aisles has four recorded dimensions, from west to east, of 23.61, 23.59, 23.57 and 23.49 metres, confirming that the nave is broader in the west and narrowest at the crossing. The north aisle has two recorded widths of 5.05 and 5.25 metres and the south aisle just one at 4.88 metres. These erratic dimensions, which have an 8% variation between minimum and maximum dimensions in the aisle bays, are a strong indication that the aisles and arcading were not laid out by the methodical application of a dimensioned rule for, if they had, there would surely have been far greater consistency.

In seeking a system for the nave-floor layout it is sensible to recognise first the dimensional variations outlined above, second, that in a floor as large as the Ely nave, some variation was likely whatever system was in use, and third, to focus on the spatial characteristics that remain unanswered by previous theories. With the phrase '*while geometrical constructions yield irrational numbers when measured, they are easy to construct and are memorable as drawings*' in mind, there are some simple spatial analyses that can be carried out, the first and most obvious being bay rhythm alignments drawn at right angles to the nave through the centres of the arcade piers, figure 24. Cylindrical piers thus sit astride solid lines and composite piers astride dashed lines to give twelve narrow bays. These bays can be thought of in other ways, as pairs (two narrow bays) between consecutive cylindrical piers and as groups of two pairs (four narrow bays) which occur three times along the nave's length and bring to mind the triplicated units described above. The nave's division into three sectors generates three root 3 rectangles between the arcades' centre lines, figure 25, and hexagons across the full width of the nave, figure 26. The short sides of the rectangle are identical to two opposite sides of the hexagon. The hexagons' vertical diameters coalesce with the intermediate cylindrical piers at the √3 rectangles' centres, thus accounting for the locations of all the nave's cylindrical piers. Alignments drawn between the hexagons' angles at the nave's outer walls and along the nave's centre line generate three diamonds that pass through the long sides of the root 3 rectangles at the locations of the composite piers, figure 27. The hexagons are also a source of small and large equilateral triangulation. The large triangles, which are shown here, have their side length in common with the long side of the √3 rectangle. With their base bisecting the arcade on one side of the nave and their apex reaching the wall on the other, the equilateral triangles span four narrow bays, or one third of the nave's length and, duplicated in mirror image, form the Star of David, figure 27. The star's four horizontal stellations are identical to the √3 rectangle's four corners. Alignments drawn between the hexagon's angles at the nave's outer walls and along the nave's centre line generate three diamonds that pass through the long sides of the √3 rectangles at the locations of the composite piers, figure 28. All of these configurations can be found individually within the compass geometry of a single daisy wheel and their triplication within a linear sequence of three interlaced wheels.

The nave floor re-appraised

Passing beneath the Monks' door daisy wheels into the south aisle of Ely's nave, the alternation of cylindrical and composite piers in the arcades is immediately visible. There are thirteen pairs between the western entrance arch and the crossing, comprising seven of cylindrical and six of composite form, the latter set diamond-wise to the line of the arcades. The thesis here is that, as with the Monk's door, the nave floor and its arcades are spatial developments emanating from daisy wheel geometry.

The daisy wheel is composed of six circles drawn around the circumference of a seventh, a rotational series of circles drawn along a circular line so that each circle passes through the axes of its neighbouring circles. Similar linear constructions can be drawn along straight lines, in which case each pair of circles will form a vesica piscis. Single circles, drawn along a centre line and forming a series of consecutive vesicas generate a simple, repetitive bay rhythm if the vesicas are bisected. The daisy wheel can be used in the same way, by multiplication along



Analysis of spatial values in the Ely nave floor

The drawings show selected alignments within the nave, commencing from the simplest repetitive bay rhythm and showing its development into groups that form proportioned thirds of the nave.

The alignments share many spatial values which strongly suggests that they arise from a common source. The configurations have been drawn to account for the slight widening of the nave from east to west.

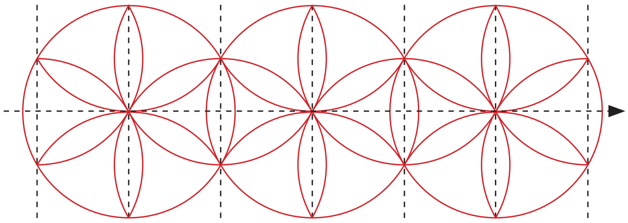
a centre line but, because its internal geometry is more complex, it offers greater geometrical potential. Because the wheel's internal structure of arcs intersect at the wheel's axis and terminate at six equidistant points around its circumference it is possible to draw linkages between all seven points to generate sub-geometries. The simplest of these is to connect all six points on the circumference to form a hexagon. Connecting every second angle of the hexagon generates an equilateral triangle while connecting the remaining angles gives a second equilateral that faces in the opposite direction. The two mirror-image equilaterals combine to form a Star of David.

It is a critical, though often unrecognised reality, that rectilinear and other angular constructions arise specifically from compass geometry. For example, a linear, three daisy wheel development, figure 29, shows that vertical lines drawn across the wheels between their petal tips and on their vertical diameters, generates a repetitive bay rhythm. At right angles to this rhythm, tangents to the daisy wheel circumferences and parallels drawn through the petal tips of all three wheels subdivide the wheels into four equal horizontal bands, figure 30. It follows that if the centre line is omitted the bands take on the ratio 1:2:1, the same aisle/nave/aisle ratio as that of the Ely floor plan. Further, if the petals on the wheel's vertical diameter are ignored, a rectangle can be drawn within each daisy wheel by connecting the four remaining petal tips (shown in graduated grey tones). This rectangle has the harmonic proportions 1:2 between its short side and diagonal. The proportion arises because the rectangle's short side is the distance between two consecutive petal tips on the wheel's circumference while its diagonal is the distance spanned by three consecutive petal tips, the central one at the wheel's axis. Because the wheel is entirely constructed from compass drawn arcs within a circle, all drawn at the same radius, it follows that any two consecutive petal tips anywhere within the wheel are a radius apart and any three consecutive tips in a straight line are a diameter, hence the ratio 1:2 and the rectangle's harmonic proportions. The rectangle is a $\sqrt{3}$ rectangle, though this term would have been unknown when the Ely nave was under construction. If the rectangle is halved along its diagonal it generates two equal 30°, 60°, 90° triangles, a perfect carpenter's or mason's square.

In contrast to the rectangular developments described above, a continuous diamond sub-geometry can be constructed within the daisy wheels by linking the poles of their vertical diameters with the points on the centre line where the bay rhythm lines intersect it, figure 31. The three linked daisy wheels, the horizontal alignments drawn through their petal tips to define the nave's band width and the diamond sub-geometry combine to form a geometrical matrix that is the bedrock of the nave's floor design, figure 32. Where the daisy wheels and their diamond sub-geometries intersect the nave band width rectangles, they pin point the locations of the piers in the arcades. The design rationale is shown more clearly in the central daisy wheel where cylindrical and composite piers are emphasised in red and blue respectively. The cylindrical piers have their locations on the daisy wheel's circumference and vertical diameter while the composite piers are placed where the diamond sub-geometry cuts the arcade alignments. The actual composite piers are also set diamond-wise in relation to the direction of the nave. It is clear that the geometrical matrix is the driving force behind the nave's design, with cylindrical piers standing on the daisy wheel's compass geometry and diagonally set composite piers standing on the diamond sub-geometry. The design process, which commences with compass drawn daisy wheels and concludes with linear and rectilinear constructions drawn along a straight edge is described precisely in the writing of Vitruvius[6] where he states that ~

' . . . . . a ground plan is made
by the proper successive use of compasses and rule,
through which we get outlines for the plane surfaces of buildings . . . . . '

29



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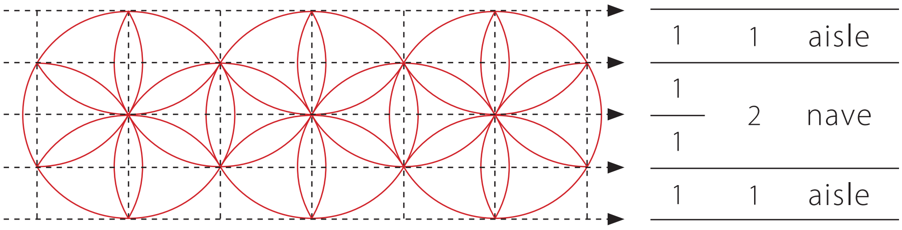

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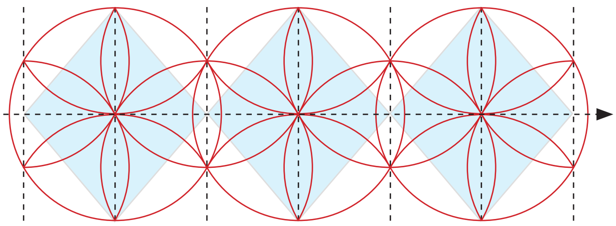

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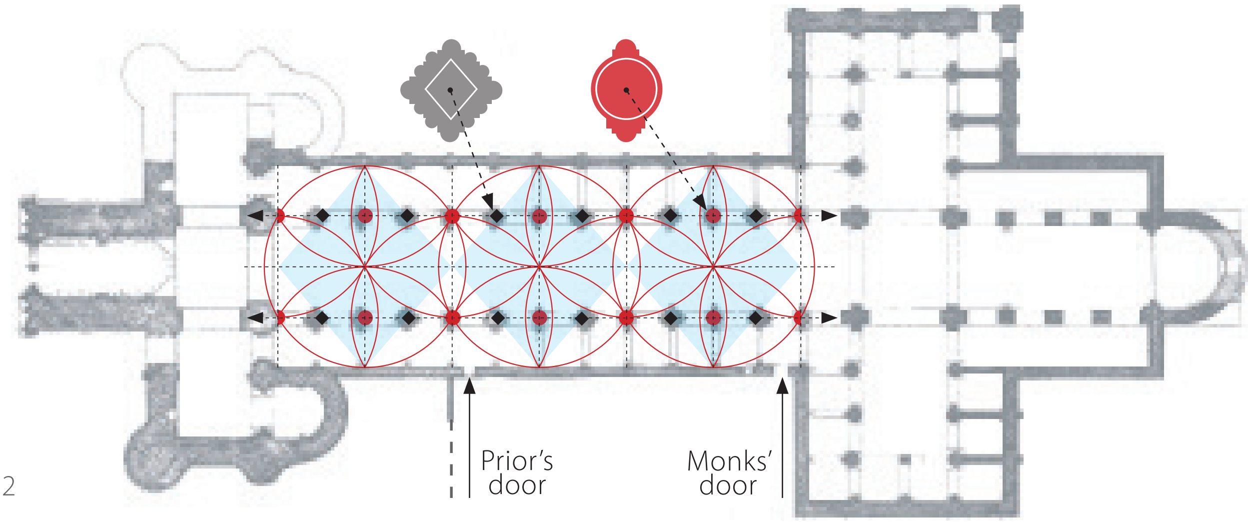


Designing the nave floor

Drawings 29, 30 and 31 show the development of a geometrical matrix that determines the alternating locations of cylindrical and angular piers within the nave's arcades. The sectional form of the piers is shown in drawing 32.

In drawing 32, the cylindrical piers, shown in red, occupy locations on the circumference and diameter of the daisy wheel while the alternating composite piers have positions on the diamond sub-geometry, each expressing their role in the harmonic relationship between circular and angular geometries.

Geometry, measurement, layout, accuracy and error

It is essential to distinguish between geometry and measurement. Geometry is a spatial language governing the relationships of locations, the linear distances between them along either straight or curved lines, and areas. In the recording of a geometrically designed building, measurement is a translation of its spatial language into the language of numbers. This translation can lead to errors, even at the most basic level. For example, in Fernie's argument for a √2 rectangle based design at Ely he defines the square root of 2 as 1.4142. This is the generally accepted figure but the reality is that the square root of 2, like the relationship between the circle's radius and circumference, is incommensurable.

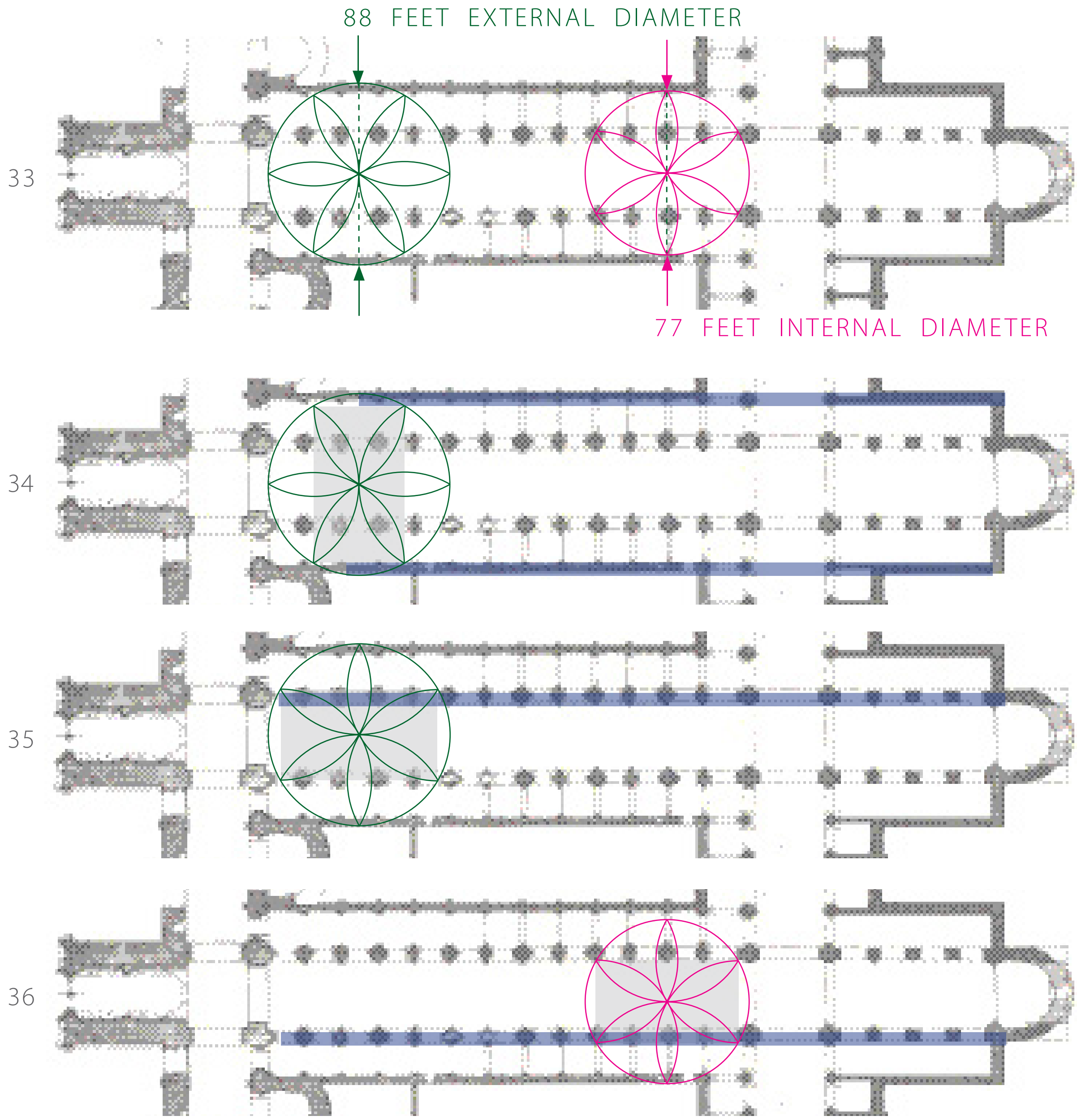
Another potential for error exists when small scale drawings are developed into full scale buildings and, in the reverse process, making a measured scale drawing of an existing building. The primary error is in the geometrical drawing itself, in the thickness of line employed. In this article the superimposed geometrical drawings have line thicknesses of 0.5, 0.75 and 1mm, line weights chosen for their legibility. However, considered in relation to the Ely scale drawing, they are as coarse as ropes. Blown up to full scale the line weight would be over 125mm for the full scale nave, giving a 5 inch error on the ground. The original measured drawing itself may, or may not, embody some drafting errors.

Other errors are inherent in the building itself, the simplest example being in the variation of mortar joints. Some recent random joint measurements taken from piers in the nave's northern arcade range from 4mm, in a vertical joint on a cylindrical pier (third from the crossing), to 32mm in a horizontal joint on a composite pier (fourth from the crossing). These discrepancies, which were visible throughout the arcades, tell their own tale regarding the accuracy of the nave's construction. These small but multiple compound errors are impossible to quantify.

Fernie gives an external nave width of 88 feet but confines his analysis of proportion to the nave's internal width of 77 feet, figure 33, an approach followed in this paper. Notably, the southern aisle is narrower than the northern aisle by a foot (300mm) and it is relevant, therefore, to test the daisy wheel geometry against the nave's 88 feet maximum width and to seek a reason for the difference in aisle width. A daisy wheel can be set to the nave's full 88 feet width and bandwidths determined between the wheel's circumference and the √3 rectangle's short sides, figure 34. The bandwidths accord well with the wall alignments. Next the 88 feet wheel can be rotated through 90˚ and the √3 rectangle is used to project the northern arcade alignments and aisle widths, figure 35. While these alignments accord well the southern alignments run out of true (and are not shown here). A smaller daisy wheel, set to the nave's internal 77 feet width, gives a more accurate alignment for the southern arcade if dimensioned from the southern wall's outer face, figure 36. The 77 feet wheel is the module tripled for the layout of the nave's cylindrical and composite piers.

The difference of 11 feet between the two wheels raises the possibility that the north and south aisles were laid out to 88 and 77 feet daisy wheel geometries respectively by independent teams of masons, the northern team using 88 feet and the southern team 77 feet when laying out the arcade and wall alignments. Such an error could easily be made. With the diameter of the wheel as the sole dimension from which the whole geometrical scheme flows, it would influence every aspect of the layout and may go some way to explain why the southern arcade is not parallel to the southern wall, the faulty alignment perhaps being realigned during construction. However, despite the deviations from parallel alignment and the individual differences in bay widths , the triplicated daisy wheel geometry can be seen as the *in principle* method of laying out the spatial relationships of the nave floor.

In the transition from scaled drawing to full scale layout on the ground, which would convert a theoretically perfect hairline geometry, drawn manually with dividers, into a large scale stone and mortar structure, it is essential for the mind to recreate the reality of the building site and to recognise how, in the hive of activity, an error in layout could be made. Translating a drawing board scale design to full scale means that the certainty of control that dividers can maintain through a series of arcs on parchment or plaster is lost when the process is carried out using cords. The 88 feet



Designing the nave wall and arcade alignments

33 The nave has an external width of 88 feet and an internal width of 77 feet.

34 The 88-feet daisy wheel generates two parallel wall bandwiths between its integral √3 rectangle and its circumference.

35 The 88-feet wheel, rotated through 90°, generates the north arcade's alignment along the upper edge of its integral √3 rectangle. The bandwidth is identical to the wall bandwidths.

36 The south arcade is closer to the aisle wall than the north arcade. The drawing shows that the south arcade was set out to the smaller, internal 77 feet daisy wheel.

external and 77 feet internal span of the Ely nave could only be dimensioned by cords which, to maintain precision over those distances, would need to be verging on rope. Rope would expand or contract in changing weather, introducing a further variability, and would be a dimensional entity in its own right. It should be remembered that in scaling up the geometry, the rope is not drawing circles. The daisy wheel is about triangulation and, although compass drawn, it is the six cardinal points on the wheel's circumference plus its central axis that allow straight line triangulations to be made. With each of the cardinal points exactly a radius apart and with three wheels joined at their petal tips, the triangulation is constant throughout the triplicated daisy-wheel construction[7].

Prior Crauden's Chapel floor

South east of the great mass of Ely Cathedral and just a stone's throw away, Prior Crauden's Chapel is diminutive in comparison. Reached by a narrow spiral stair to first floor level, the chapel is little more than a large room, but it houses a remarkable tile pavement, set at two levels, the sanctuary floor two steps higher than the remainder. The geometrical scheme works better here because the tiles were almost certainly designed ta full scale, one third of the triple unit being just 20 inches square. A full scale design has no transitions to make and, therefore, little chance of error.

There are three visual elements to the sanctuary floor: heraldic lions at different scales, geometrical patterns at different scales and, at the centre of the design, figurative representations of Adam, Eve and the serpent with Eve passing Adam the fateful fruit. The figures stand with their feet at the edge of the steps so they were clearly intended to be seen from the chapel's lower level and, from this point of view, they are flanked to left and right by two rectangular strips of geometrical tiling that include solid and linear hexagons, diamonds and triangles. These are the tiles that follow the Ely nave as examples of daisy wheel design and the triplicated daisy wheel proportional module in particular but they are defined by different and more complex sub-geometries, figure 36. The chapel's pavement dates from around 1345, about seventy years after the Cosmati pavement laid at Westminster in 1268, which also includes geometrical patterns derived from daisy wheel geometry.[8]

In the first stage of the design, figure 37, pairs of equilateral triangles are drawn between the petal tips in each daisy wheel so that they overlap in mirror image to form Stars of David. Because the daisy wheels connect at their petal tips it follows that the stars also connect at their stellations to form a horizontal star band width. This band is identical to the nave band width in the cathedral though on a miniscule scale, just 20 inches (510mm) wide, and the important recognition is that both scales have identical proportional values. It can be seen that where the stars meet, a diamond is formed between them, figure 38. A distinction must be made between these diamonds as part of the pavemant's design and as actual tiles. If considered as actual tiles, the two end diamonds extend beyond the boundary of the triple daisy wheels and, in doing so, generate a slightly longer rectangle than the basic daisy-wheel geometry of figure 37. Four further diamond tiles can be placed in the remaining angles of the stars, on the right of the drawing, but these remain within the daisy-wheel bandwidth. A further sub-geometry completes the corners of the band width by introducing a smaller diamond and triangles, figure 39. The smaller diamond is exactly half the height and width of the larger ones and is therefore a quarter of their area and harmonically related. It can be seen in the drawing and photograph that all diamonds are composed of double equilateral triangles joined base to base. Once all the diamonds are placed in relation to the stars, they coalesce into the greater forms of hexagons though each pair of great hexagons has a shared diamond in common. The great hexagons form a backdrop to the stars which, in their turn, are a backdrop for a small hexagon and a ring of six small equilateral triangles, figure 40.

Before continuing it is necessary to describe the star in terms of the two equilateral triangles that form it: that with its point at the top of the daisy wheel as an *up* equilateral and that with its point at the base of the daisy wheel as a *down* equilateral. So, in the left hand daisy-wheel, two points of intersection occur where the up and down equilaterals intersect and two more occur at the ends of

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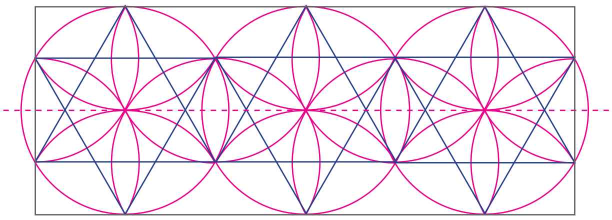

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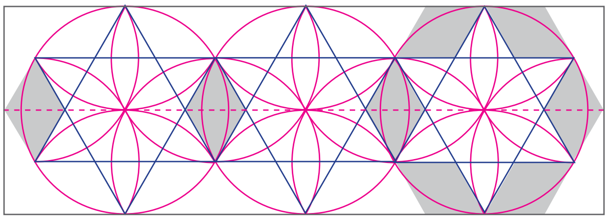

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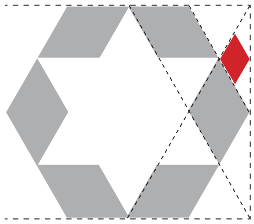

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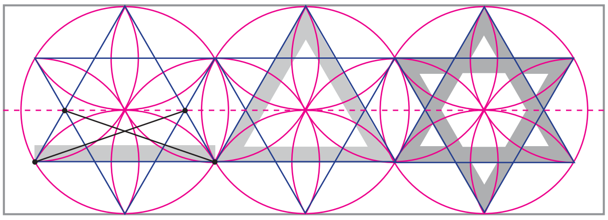

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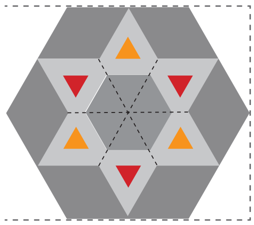

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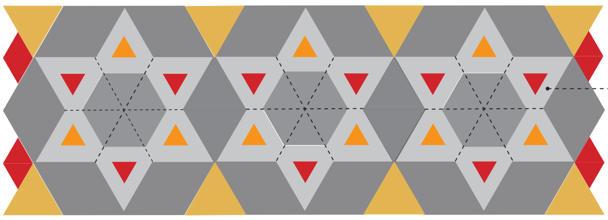

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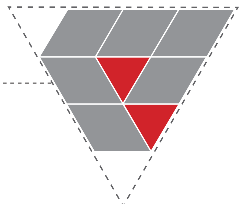


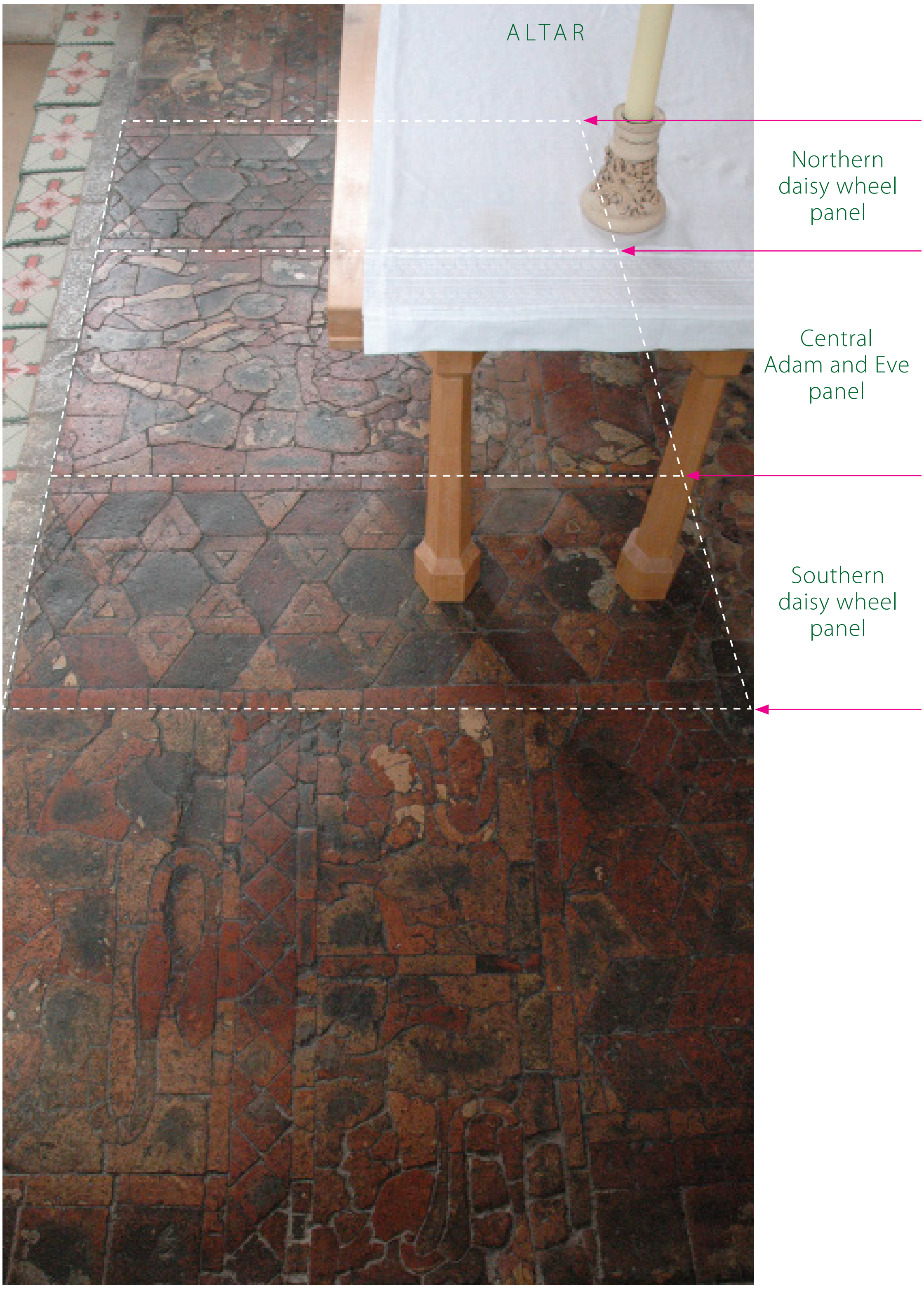
Designing Prior Crauden's Chapel pavement panel

36 A triple tile panel beneath the altar table 37-38 Developing Stars of David and diamonds from the daisy wheels 39 Detail of the panel's end resolution 40 - 41 Developing the Star of David bandwidths, internal hexagon and small equilateral triangles 42 Reconstruction of the tile panel showing the intricacy of the pattern 43 Truncated equilateral triangles that form the star within each great hexagon

the up equilateral's base line, the positions marked by four black points. Diagonals drawn between the four points cut the down equilateral in two places and it is between these places and the up equilateral's base line that a bandwidth for the star can be established. This construction is repeated on all sides of the up equilateral, as shown in the central daisy wheel, and repeated for the down equilateral, as shown in the right hand wheel. The bandwidths automatically generate the star's small internal hexagon and the ring of small equilateral triangles that surround it, in the right hand wheel. The hexagon's sides are 4 inches (102mm) in length. In the final stage of the development, figure 41, radials from the axis of the hexagon cut the star's band width to produce six truncated equilateral triangles, the shapes of the actual tiles. However, there is one more stage in the pattern's development, almost certainly carried out as the tiles were manufactured. The star's bottom right stellation shows a further set of divisions, drawn as parallels to the central triangle, that give three small diamonds on one side, two on the second and one and a half on the third. These lines are knife cut into the tile's surface. The harmonic geometrical intricacy of the full tile scheme, figure 42, is maintained down to the finest detail, figure 43.

44

The entire floor of Prior Crauden's Chapel is laid with geometrical tiles on two levels. The higher, sanctuary floor level, which is raised by two steps, has a central panel of anthropomorphic tiles depicting Adam and Eve, figure 44. The geometrical tile panels described above in drawings 36 - 43 are located at either side of the Adam and Eve panel. The remainder of the sanctuary floor has other geometrical tile schemes. Figure 45 shows the central Adam and Eve panel and the geometrical panels that flank it, seen from the south side of the altar and partly obscured by it. The boundary stonework of the top step can be seen to the left, above the embroidered kneelers resting on a lower step.


ALTAR
Northern daisy wheel panel
Central Adam and Eve panel
Southern daisy wheel panel

45

The Barley Barn floor

The Barley Barn at Cressing Temple, figure 46, was built by the Knights Templar in 1220, the first of two great aisled barns constructed at their Essex estate. The barn has seven bays, five of which are of equal width, with narrower bays concluding the barn at either end. The great waggon porch into the midstrey is later and not part of this analysis. The midstrey, which is central to the five equal bays, has a pair of bays at either side, each pair forming a nave rectangle bounded by three pairs of massive arcade posts. These nave floor rectangles were shown by Adrian Gibson to have the harmonic ratio 1:2 between their short side (across the barn) and their diagonal (from the first arcade post on one side of the nave to the third on the opposite side). [9] He found the same ratios in the aisles but these were within single bays and were half the length and width of the nave ratios, figure 47. The nave and aisle ratios, which are identical proportionally but of different scale, have their genesis in compass geometry. A rectangle drawn through all six of the daisy wheel's petal tips, figure 48, can be halved vertically by connecting the tips on the wheel's vertical axis and divided into three horizontal bands by connecting the remaining four. The bands, in the ratios 1:2:1 across the barn's width, generate one large central rectangle with two small rectangles at either side. Drawing diagonals across each of the rectangles generates identical proportional triangulation to that of the barn's floor. The triangulation gives perfect set square angles of 30°, 60° and 90°, figure 49. It is noticeable that, as in the Ely nave geometry, the nave begins and ends at two petal tips rather than at the circumference of the daisy wheel's circle. This is a practical use of the geometry because it is easier and more accurate to plot a bay rhythm between two fixed points than as a tangent to a circle. This is also why the three daisy wheels connect at their petal tips.

The floor plan, although smaller in area than the Ely nave, has identical proportions and can be generated from the same triple daisy wheel geometry. Once the three daisy wheels are constructed, arcade alignments can be drawn through their horizontal petal tips, along the barn's length, figure 50. The construction of a diamond grid cuts the arcade alignments at twelve points of intersection, six along each side of the barn, and lines drawn through these points across the barn's

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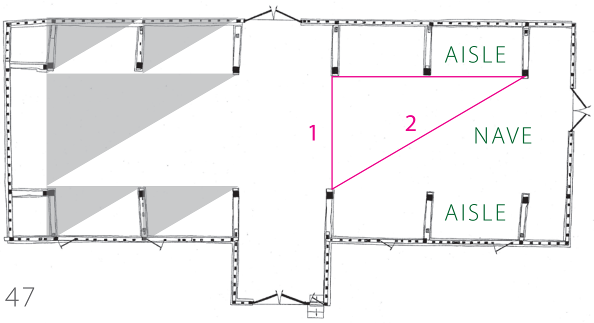

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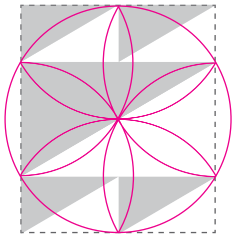

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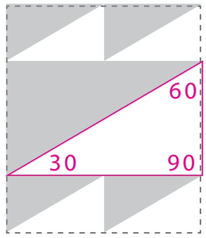

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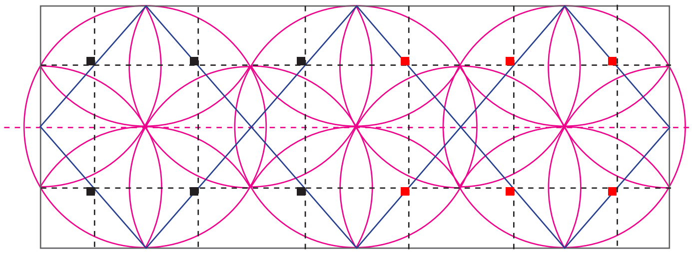

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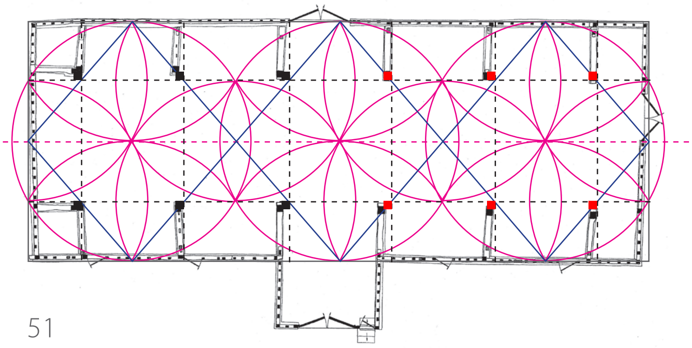

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Designing the Barley Barn floor

46 The barn's interior. 47 The measured floor plan showing the 1:2 ratios discovered by the late Adrian Gibson. 48 The author's proof that the 1:2 ratios had their origin in the daisy wheel 49 The presence of 30°, 60°, 90° triangulation. 50 The geometrical floor plan with aisle posts placed in the same positions as Ely Cathedral nave's composite piers. 51 The geometrical floor plan superimposed on the measured drawing. The daisy wheel diameter and width of the barn is three medieval Rods or 49 feet 6 inches. A single Rod is 16½ feet.

width generate the building's bay rhythm of five equal bays with narrower bays at either end. The arcade posts are placed at the intersection of the arcade alignments and the bay rhythm lines and it is noticeable that they are all placed to the same side of the bay rhythm lines (on the left in the drawing). It is conventional carpentry practice for bay frames to be placed adjacent to the geometrical lines that define them but it can cause difficulties in measured analysis. This is because, when measured, the two end bays are unequal, the reason being that there is an arcade post in one geometrical end bay but not in the other. At Cressing, it was thought for some time that this discrepancy resulted from the narrower end bay's gable wall having been rebuilt closer to the nearest arcade posts or even that both end bays had been reconstructed to a narrower bay width than the other bays along the barn's length. This demonstrates that measurements, however accurately taken, can give erroneous information. Geometrical analysis, conversely, gives spatial information and, in the case of the barn, a more accurate picture because it defines a reason for the different narrow bay widths. But, because the barn's designer was a carpenter, understanding carpentry layout and framing methods adds further, essential practical insights, figure 51.

Comparing the Ely nave and Barley Barn geometrical floors, the significant difference is that all fourteen of the Ely cylindrical pier locations, including the semi-piers at each end of the nave, are absent in the layout of the barn. There are sound reasons for this. The cathedral is far greater in scale and built from stone, the barn smaller and built from timber. The great weight of the cathedral's masonry, constructed on ground, triforium and clerestorey levels, clearly needs greater physical support than the structure of the barn, which is essentially a space frame pegged together at cardinal points in its structure. It is noticeable that, like the angular piers at Ely, the square aisle posts are placed on the angular geometry.

17 Court Street, Nayland, Suffolk

The village of Nayland, which is in the richly timber-framed area that spreads along both sides of the Essex-Suffolk border, is home to four unusual buildings. These pairs of rentable properties of the late fourteenth or early fifteenth century can be found in Bear Street, Birch Street, Fen Street and Court Street[10]. The facade of 17 Court Street, figure 52, is deceptive for, although the two medieval renters are now combined into a single house, each of the originals were just 18 feet long, with each frontage housing a hall, cross passage and service area, the front of which was possibly a shop. The two diminutive smoke blackened halls, a mere 8½ feet in length, were augmented by an aisle across the rear of the building. Over time, the original long walls were raised to incorporate a first floor and the rear aisle metamorphosed into a cat slide extension. The true scale of the building can be gauged by standing beside the front doors. The left doorhead drip is the height of a six foot man while the right doorhead reaches only to the shoulder. Both doors still open into cross passages. Importantly, from a design-research perspective, there is a measured floor plan of the houses that make up today's 17 Court Street[11].

Like modern semi-detached houses, each pair is constructed in mirror image either side of a central party wall, yet the geometrical foundation upon which they stand is a linear, triple daisy wheel configuration identical to that of the Ely nave, Prior Crauden's Chapel tiles and the Barley Barn at Cressing. However, the sub-geometry is quite different, simpler and, unlike the angular sub-geometries of the previous examples, employs compass drawn circles to generate new cardinal points of intersection in the daisy wheel alignment. Figure 53 shows two small circles, drawn in blue within the outer daisy wheels so that they touch the circumference of the central wheel. They cut the outer daisy wheel's petals at twelve points of intersection, four of which are marked by black dots and are crucial to the horizontal bandwidth of the aisle. In figure 54, further intersections marked with red dots, define the vertical bandwidths of the cross passages within each semi-detached house. The aisle running across the rear of both houses and the cross passages of both houses are shown in blue tone in figure 54 and projected down into the floor plan in figure 55. The floor rectangle of the building is defined on the long walls by tangents to the three daisy wheels and, at the short end walls, through two of the daisy wheel's petal tips, a construction that automatically generates right angles at the building's four corners, figures 53 and 54.

There is an interesting lesson in the geometry of the arcade plate's alignment where it passes through points on the daisy wheel petals. It can be seen, in figure 54, that this alignment passes very close to, but not through, the daisy wheel petal tips at the wheels' circumference. In daisy wheel geometry generally, the petal tips would have been the expected positions for an alignment, so the chosen alignment reveals the carpenter's thought process. The design proceeds a step at a time, alternating between linear and compass drawing. It commences with a straight centre line on which the compass daisy wheels are drawn. The daisy wheels, in turn, define the building's angular perimeter. A compass sub-geometry is then drawn and from this the angular cross passages and linear arcade plate can be drawn. So the design follows the path from linear to compass to rectangle to compass to linear in a carefully orchestrated relationship between circularity and angularity. Without the underlying geometrical grid, which imparts a proportional harmony to the building's floor plan, it is difficult to comprehend why the particular configuration of external and internal walls would be in the positions they are.

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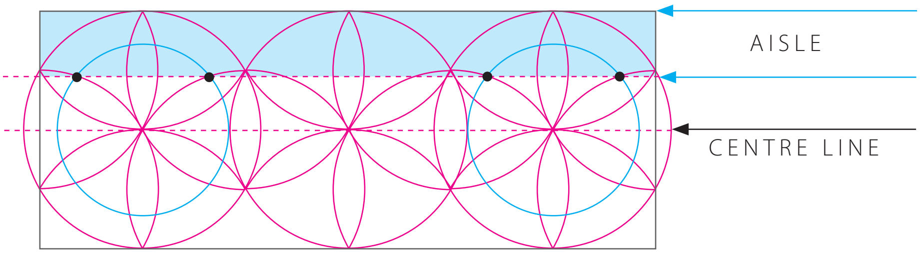

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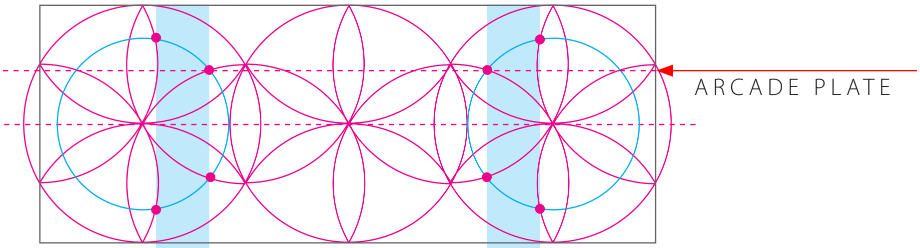

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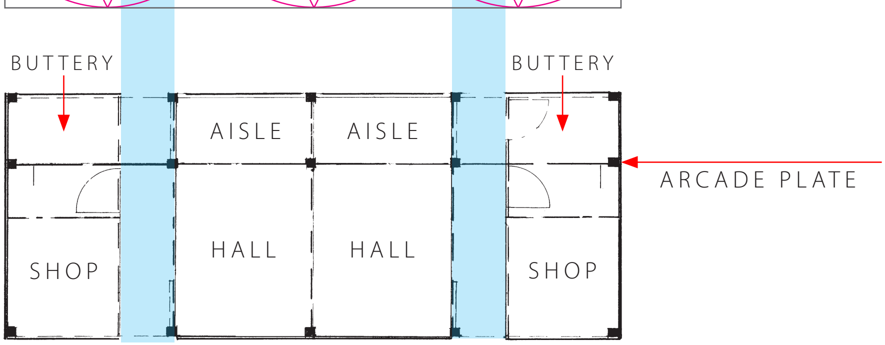

Designing the Nayland mirror-imaged halls

52 17 Court Street, Nayland 53 The geometrical floor plan showing secondary circles (in blue) drawn to touch the overlapped vertical vesicas. The blue circle cuts the daisy wheel's arcs at cardinal intersections that define the rear aisle and cross passages 54 The alignments of the cross passages and arcade plate 55 The floor plan showing the mirror-image layout of the two hall houses, with the geometrical passages in drawing 54 extended into the floor plan. The halls are diminutive, just 8 feet 6 inches wide.

The Governor's House, Jamestown, Virginia

It is a quirk of history that the Governor's House, built at Jamestown, Virginia in 1610 and the most recent of the examples in this paper, is the only one not to have survived to the present day as a standing building. Conversely, where the designers and builders of the other examples are all now lost, the names of the four Jamestown carpenters who cut and assembled the Governor's House are known: William Laxton (or Laxon), John Laydon, Edward Posing (or Pising) and Robert Small who all came from the Suffolk area of England. There is also a brief description, 'Jamestown . . . two rows of fair cottages, 2 storey with corn loft'.[12] However, what does survive is the recently discovered footprint of the house, recovered by archaeologists from the Association for the Preservation of Virginia Antiquities.[13] The Governor's House footprint indicates a building mirrored to either side of a central party wall as well as from front to back, with the entrances to the two sectors on opposite sides of the building, a symmetry also applied to the chimneys. Significantly, the two rooms either side of the central party wall were 11 feet wide, two thirds of the medieval rod (16½ feet), figure 56. The rod's relationship to feet and its division into thirds are shown in figure 57. Dimensions developed from an 11 base are common in the medieval period, as has been seen in Ely Cathedral. Ludlow burgage plots are 33 feet, or a double rod, in width. Adding the widths of the two central rooms gave a dimension of 22 feet, a measurement with obvious 11 base resonance. Developing a triple daisy wheel grid scaled to 11 feet radius (22 feet diameter), figure 58 and projecting it onto the footprint, figure 59, gives the building's length to the inner face of the end wall sill beams and generates precise alignments for the mirrored entrance passages and chimneys, determined by tangents to the vertical vesicas in the two outer daisy wheels.

However, although this compass geometry was 2 feet wider than the footprint at ground level, it was clear that the building could have been designed 22 feet wide at wall plate level and diminished geometrically to 20 feet at floor level to give the footprint, a jetty at first floor level accounting for the dimensional difference. There is an interesting parallel to this in the reconstruction of the Globe Theatre in London, built first in 1599, damaged by fire in 1613 and rebuilt in 1614 just four years after the Governor's house. Jon Greenfield has written,

> . . . studies tended to concentrate analysis exclusively on the lower members of the timber frame, the sill beams. Peter Streete, the Globe's mas ter carpenter would have been thinking beyond this at the outset. His first task . . . would have been to set out sill beam and wall plate together, the sill being the lowest component of the structural frame and wall plate being the highest. So Peter Streete had in his mind not just one set of dimensions (for setting out the sill) but a second set for the wall plate too, both of equal importance. The possible presence of jetties at the storey heights . . . means that the setting out of the wall plate and the setting out of the sill could be quite different.[14]

A rectangle connecting four of the central daisy wheel's petal tips can be used to dimension a smaller blue circle within the wheel, both shown in blue in figure 58. It is this circle that defines the narrower building width at ground level while the full daisy wheel oversails it to establish the jetty. Figure 59 shows how the distance from the back wall to the front circumference of the small blue circle at ground level is 20 feet, identical to the footprint. The Jamestown footprint differs from the previous examples in one respect, that the building's length extends beyond the

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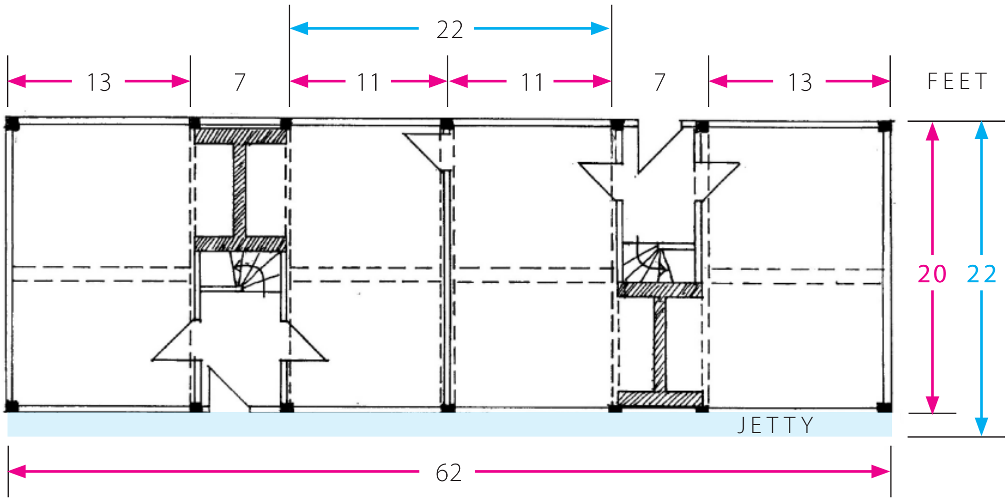

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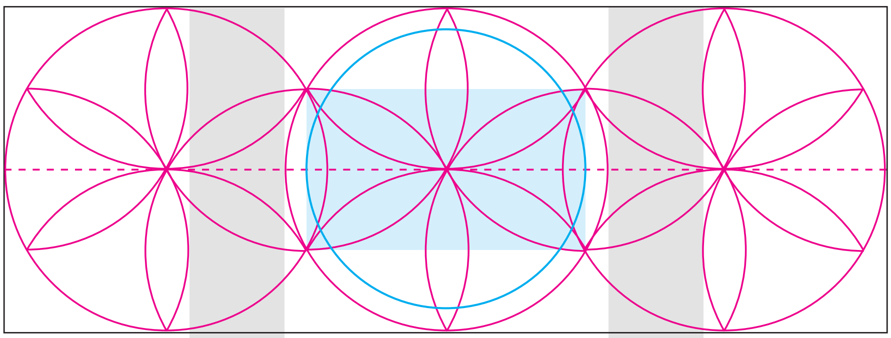
				1	2	**Rods**
$1^1/_{32}$	$2^1/_{16}$	$4^1/_8$	$8^1/_4$	$16^1/_2$	33	**Feet**
		$5^1/_2$	**11**	$16^1/_2$		$^1/_3$ **Rod**

58



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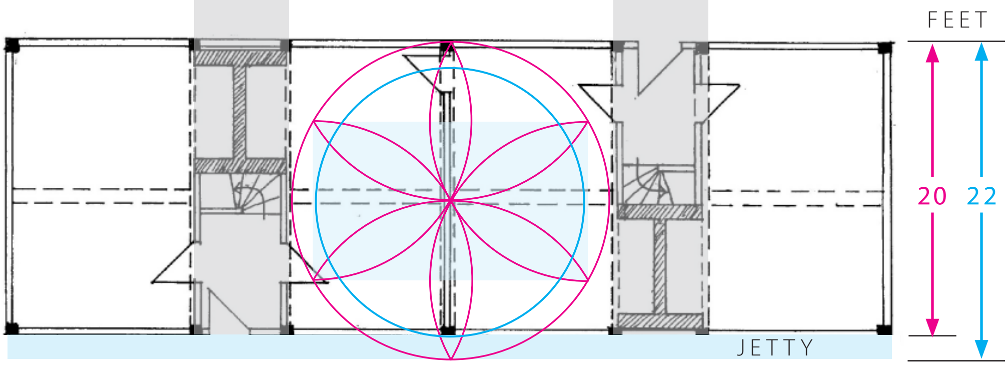


outer daisy wheel's petal tips as far as the circles' circumferences.This means, in proportional terms, that the Governor's House is slightly longer in relation to its maximum width at wall plate level than the other examples. This is purely a matter of choice on the part of the carpenters and can be easily attained by taking a centre line measurement from both the end daisy wheels, from axis to circumference, and repeating it on the front and rear wall alignments. In either case the geometrical source remains the same.

Daisy wheel design in a broader context

A design system spanning four hundred years, from Ely to Jamestown, might seem improbable in our modern world of constant change. Without the momentum of mechanisation, automation and electronics, a world where progress was attained through manual labour and transport by horse, ox or water saw slower evolution and the maintenance of viable design and construction procedures over long periods of time.

The rectilinear proportional designs outlined above are, in fact, a small sample of daisy wheel design, grouped together because they provide evidence for the employment of a specific design strategy. The rationale is simple, that the daisy wheel's intrinsic triangulation and the design potential embodied within it, can be extended by repitition any number of times along a centre line. The daisy wheels in an extended sequence are connected at their petal tips precisely because the tips are also focal points in each wheel's internal triangulation. The linkage therefore extends the triangulation over a greater distance. The crucial decisions are the number of wheels to be connected and the orientation of the wheels within the extended bandwidth. All five examples in this paper have the same orientation, with two of the wheel's petals occupying positions on the vertical diameter, either side of the axis, and extended through three wheels. As is clear from the drawings this triple sequence generates the proportions of a specific long rectangle, suited to the functions of a cathedral nave, a barn with a central midstrey, or mirrored, semi-detached housing with double passages and entrances.

Although the focus here is on theses examples it is worth mentioning in passing that other proportional rectangles can be derived from daisy wheel sequences and that these may be on a different orientation. In north Wales, the Landmark Trust property, Dolbelydr (Welsh dol = meadow, pelydr = radiant) is designed on a three daisy wheel sequence with the wheels' diameters oriented horizontally. This gives a greater degree of overlap between the wheels which, in turn, compresses the length of the rectangle, making the building shorter in relation to its width than the examples above. However, this is compensated for by the fact that Dolbelydr is an early storied house, so the shortened proportions are duplicated one above the other on the ground and first floors to give a substantial floor area in total. Dolbelydr has been dendrochronologically dated to 1578[15]. Conversely, Leigh Court Barn near Worcester maintains the same orientation as the examples given above, but extends on plan to a five wheel sequence with the wheel's radius of 16½ feet giving a 33 feet diameter, the barn's width of 2 medieval rods. Each of the five daisy wheels is divided into two sectors by its vertical diameter, each sector being one bay of the barn, the five wheels therefore generating ten bays in total. A ten bay frame has eleven trusses: two end walls and nine bay trusses, all nine of which, at Leigh Court, are framed as cruck pairs. Leigh Court barn was built for the monks of Pershore Abbey in 1344. Both of these variants, therefore, fall within the same time scale as the five examples described here. What emerges overall is a geometrical methodology for setting out daisy wheel based triangulation on the gound in order to establish proportionally controlled floor plans of varying lengths, an essential prerequisite, once the section has been designed, to calculating the volume of stone or timber needed for the construction of each building.

However, daisy wheel geometry can be found in England almost a thousand years earlier than the Ely nave, carved on Roman military tombstones. Gaius Saufeius, a soldier in the IX Hispana at Lincoln, was commemorated by a tombstone decorated with three precisely carved individual daisy wheels above the inscription recording his life. The stone's form and inscription can be designed using a single daisy wheel. On the opposite side of the country at Chester the tomb of Aelius Claudianus features a band of five overlapped daisy wheels, all of identical radius with each passing through the axis of its neighbours. A rectangle drawn around the wheels gives the overall proportions of the whole stone. The five wheels are therefore both a decorative band across the head of the stone and, simultaneously, the reason for its external proportions[16]. At Fishbourne Palace near Chichester in Sussex the daisy wheel is one of a number of geometrical configurations that appear in the mosaic floors, used there as a construction grid for pattern making. At Ebbsfleet, near Gravesend in Kent, archaeologists recently discovered the remains of an Anglo-Saxon water mill from 700 AD which had a full seven circle daisy wheel finely scribed into the upper boarding of one of two large timber chutes that focussed the force of water onto the mill wheel[17]. The geometry of the daisy wheel allows for the construction of either six or twelve radials from the primary circle's axis, all at either 30° or 60° intervals and exactly the configuration required for the paddle arms of a water wheel. Although the actual wheel was missing at Ebbsfleet a similar mill discovered at Tamworth retained its twelve paddled water wheel. The Ebbsfleet mill is the earliest known horizontal water mill so far found in England.

From much more recent times there is an unusual example of daisy wheel building design in the form of Shackleton's Nimrod Hut, constructed by Humphrey's Limited of Knightsbridge to Shackleton's own design for the British Antarctic Expedition of 1906[18]. Shackleton's floor dimensions (33 x 19 feet) give a diagonal of 38 feet so that the short side to diagonal ratio of 19 : 38 (or 1: 2), gives the harmonic proportional ratio found by connecting four of the daisy wheel's six petal tips. The three dimensional form of the hut also follows daisy wheel design principles in every respect and 33 feet is, of course, the medieval double rod. Shackleton's Nimrod Hut is, like Jamestown's early buildings, an English design built on another continent.

By far the greatest evidence of daisy wheels can be found scribed, predominantly by dividers and occassionally by compass race knife, in the surfaces of timber framed buildings. Although, regretably, no records have been kept of their locations, scribed wheels are found in numbers in all parts of the country. They are so commonly found in timber-frames that a building without them is the exception rather than the rule.[19] These no-assembly marks can be orthodox daisy wheels, seven circle constructions with a central diasy wheel, other types of compass configurations including a small number of non-daisy wheel constructions that yield square or rectangular geometries and incomplete, or shorthand, daisy wheels referred to by modern frame carpenters as cut circles. Cut circles usually show the primary circle, cut by six small arcs at equal distances around the circumference, the six points which, in conjunction with the wheel's axis, allow for the construction of equilateral triangulation. Some cut circles have only three cuts on the primary circle which, when connected, allow angles including a right angle to be constructed. Others have four cuts and these provide the connections necessary for the 1:2 ratio rectangle.

Pre-numerate, pre-industrial design

There is a school of thought that all daisy wheel and related geometrical symbols have some ritual purpose. This may or may not be the case. The argument here focusses solely on the design capacity of daisy wheel and cut circle geometries found scribed into, predominantly, timber-framed buildings. The question arises, why should these marks be so prevalent in timber frames? While the design function of the daisy wheel has already been demonstrated, the answer to this question becomes clearer if the character of the marks is examined in detail. All marks scribed with dividers (which are needle sharp) are extremely fine and often invisible unless a strong light is shone obliquely across the surface of the timber so that shadows are cast from the edges of the mark. Dividers are carpenters' tools and are used to measure and transmit the depths, dimensions and positions of joints to be cut from one timber to another. These positions, in turn, are often extended across timbers with a scratch awl along a straight edge or square, marks often seen, for example, as vertical lines at either side of joists where they are jointed into a ceiling beam, the lines marking the width of the mortices. The lines are usually scribed right across the beam and it is the sector undisturbed by cutting the mortice that remains to be seen after the joints are assembled. A second and heavier type of line is scribed using a compass race knife, a small, fixed radius tool with a compass pin on one arm and a miniature gouge on the other. The tool also has a small retractable arm for drag-gouging straight lines. In contrast to the delicacy of scribed divider lines, the race knife cuts a line of approximately a sixteenth of an inch in width which is clearly visible as a small half round channel. This is because the race knife is used to code the timbers of individual trusses, long walls and roof planes within the overall frame, after they have been assessed for correct fit in a test assembly. The test assemblies can then be dismantled, transported to site, and re-assembled by reference to the marks. To serve this purpose, the marks scribed with the race knife must be clearly visible and, because it is a fixed radius tool, it follows that the marks produced with it are circles and half circles or, in large buildings, multiples of them.

At Lower Brockhampton in Worcestershire, for example, the two storey jettied gatehouse that also acts as a bridge across the manor house moat has half circle race knife marks on one doorpost and full circle vesica marks on the other, clearly distinguishing the opposite sides of the frame. Individual timbers within the frame are numbered using the retractable arm to drag linear gouge marks approximate to Roman numerals. That these timbers are all identified by race knife compass arcs, linear drag cuts, scratch awl lines indicating locations of joints and, further, are drilled to receive pegs that will hold the erected frame together, are all indicators of, in modern phraseology, a kit form building. Such a building must be planned in order to establish what comprises the kit is and where each component is located. In fact the planning goes back further for it is essential to make a cutting list before entering the woodland for felling and it is impossible to compile a cutting list without the existence of a plan. All the marks found on timber frames speak loudly of the work of carpenters, craftsmen who used dividers and race knives in their daily work. This repertoire of marks can be viewed as a historic, nationwide archive that bears witness to the existence of a highly organised design-and-build methodology. The argument here is that, in a pre-industial, pre-numerate society where manual skills were widespread, geometry was the state of the art design system. It needed only dividers, straight edge (or square) and scribe, tools that were simple to use and widely available. The method was free from mathematical calculation because all design evolved from an initial radius chosen to fit the scale of the job in hand.

The evidence of daisy wheels and related geometrical symbols, divider-scribed and race-knife-cut into timber frames or chisel-cut into masonry buildings is inescapable. The former are found throughout the country in the widest range of buildings including houses and barns of humble status while the latter tend to be found in high status masonry buildings. The five examples presented here span a wide spectrum of status from Ely Cathedral down to the tiny Nayland hall houses and of scale, from Ely's 200 x 77 feet nave to the 5 x 1½ feet tile panels in Prior Crauden's Chapel. While the daisy wheel's precision presence at Ely both suggests and provides the geometrical start point for proportional analysis, its absence from other buildings does not preclude the likelihood that it was used. The reverse is true. If a building's proportions on plan accurately fit a specific geometry, that geometry is the most credible reason for the building's proportions.

In conclusion, the examples of daisy wheel geometrical design described above can be seen as a specific design application for the proportional layout of linear buildings or, in the case of the Ely nave, a linear component within a cruciform architectural scheme. To be absolutely clear, the geometrical design is the blueprint for laying out each of the ground plans of the buildings in question, irrespective of their scale and, while the configurations shown in this paper can be reached by other geometrical routes, the triple daisy-wheel module is the simplest means of reaching the blueprint. It has the advantage that it can be drawn to a single radius, chosen to fit the specific building, and thus eliminates the need for mathematical calculation. At Ely, the likelihood of its use is endorsed by the powerful presence of the daisy wheels carved into the cathedral's fabric. The fact that, even in this small sample, the geometrical blueprint is found in buildings across such a wide social spectrum suggests the existence of a design methodology that was common knowledge among carpenters and masons at all levels of society; that this knowledge was widespread; and that it was applied to even the simplest of buildings. This challenges our current understanding of the term vernacular.

Postscript: a Frame for Cecil and Adrian

After the presentation of this research at the SAH / VAG Symposium in London in May 2008 an opportunity arose to submit the proportional design systems outlined above to a practical test. I was asked to design a small, single bay gardener's shelter for the Elizabethan walled garden at Cressing Temple in Essex, using geometrical principles. I decided to use the same baseline daisy wheel geometry that underpins the floor plan of the Barley Barn. The project was run by the Carpenters' Fellowship with timber supplied from local woodland by Essex County Council. My colleagues, William Clement Smith from Suffolk and Joel Hendry from Dartmoor, project manager and lead carpenter respectively, and I co-ran an eight day timber framing course commencing from timber in the round. There were no petrol or electrically driven power tools on site and no measurements or modern dimensioned rulers or tapes were used. Conversion was undertaken with hand held axes and trestle saws. Using two rods of 7½ feet radius we set out a daisy wheel triangulation on the ground with the geometry then plumbed up to the timber layups. Twenty carpenters from Canada, the USA, Europe and the UK, ranging from novices to established professionals, cut and raised the frame in eight days. The geometrical design method ran smoothly from start to finish, proving that a building can be designed to geometrical proportions from a radius alone. A commemorative inscription to Cecil Hewett and Adrian Gibson, who both had a long association with Cressing Temple, was chisel-cut into the frame by Rupert Newman of Westwind Oak Buildings, Bristol, the wording reading simply ~

a Frame for Cecil and Adrian

Footnotes

1 John Maddison cites George Zarnecki in dating the Monks' Door to 1135. The foliage replicates that found in an illuminated manuscript produced in the Ely scriptorium at that date. See, John Maddison, *Ely Cathedral, Design and Meaning* (Ely, 2000), p. 31.

2 W. P. Griffith, in Joseph Gwilt, *The Encyclopaedia of Architecture* (London 1867), revised by Wyatt Papworth (New York), 1982), p. 974.

3 Eric Fernie, 'Observations on the Norman Plan of Ely Cathedral', in *British Archaeological Association Conference Transactions for the year 1976 II: Medieval Art and Architecture at Ely Cathedral*, eds Nicola Coldstream and Peter Draper, 1979, pp. 1-7.

4 Nicola Coldstream, *Medieval Craftsmen: Masons and Sculptors* (London, 1991), p. 37.

5 Maddison, *Ely*, pp. 15-16.

6 Vitruvius, *The Ten Books of Architecture*, translated by Morris Hickey Morgan, (New York, 1960), pp. 13-14.

7 Triangulation can be developed as layout on the ground by peg and cord or by stepping out along lines. Stepping out is usually developed along a chalk line, either on the ground, on masonry or along timbers.

8 For the floor of Prior Crauden's Chapel see eds Coldstream and Draper, BAA, plate XX. For the Cosmati pavement in Westminster Abbey see Richard Foster, Patterns of Thought (London, 1991) p. 14.

9 Adrian Gibson, 'The Constructive Geometry in the Design of the Thirteenth Century Barns at Cressing Temple', *Essex Archaeology and History*, 25 (1994), pp. 107-12.

10 These Nayland houses were brought to my attention by Suffolk carpenter Rick Lewis and are described in Leigh Alston et al., *A Walk Around Historic Nayland* (Nayland, 2000).

11 The plan of 17 Court Street was sent to me by Adrian Gibson.

12 This quote was passed to me by the Association for the Preservation of Virginia Antiquities.

13 The footprint was brought to my notice by Norman Guiver, Chairman of the UK Carpenters' Fellowship, who asked me to look for evidence of any geometrical proportions as the Carpenters' Fellowship and their American counterpart, the Timber Framers Guild, were planning a joint reconstruction of the building using English carpentry techniques. Philip Aitken drew a perspective reconstruction of the house based on its footprint and houses of the same date and type in Suffolk. Being a storeyed house, his representation was jettied at first-floor level on the front elevation.

14 Jon Greenfield, '*Timber Framing*', in eds J. R. Mulryne and Margaret Shewring, *Shakespeare's Globe Rebuilt* (Cambridge, 1997), pp. 97-100

15 For this date I am grateful to Andrew Thomas, the architect for repairs at Dolbelydr carried out by the Landmark Trust.

16 Gaius Saufeius' and Aelius Claudianus' stones can be found in the British Museum and the Chester's Grosvenor Museum respectively. The British Museum also has examples of Roman dividers and squares.

17 I am grateful to Damian Goodburn for information about the Ebbsfleet archaeology.

18 Gordon Macdonald, 'Extreme Conservation: Saving Shackleton's Hut' and 'Conservation of Shackleton's Hut' *Mortice and Tenon*, 22 (Winter 2005), p. 11and 24 (Summer, 2006), pp. 2-5.

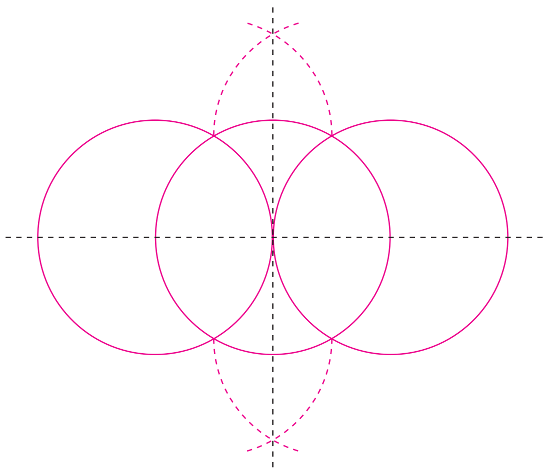
19 Peter Smith, the author of *Houses of the Welsh Countryside: A Study in Historical Geography* (London, 1975), has told me that he has seen thousands, many of them in buildings of humble status.

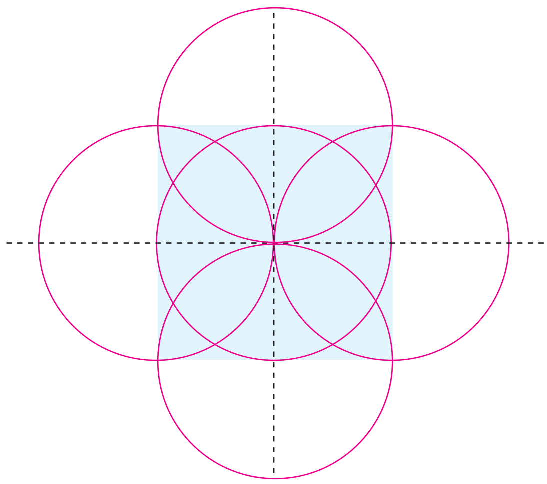
Additional Notes

In the symposium publication, *Built from Below: British Architecture and the Vernacular*, the economics of production dictated that each of the ten authors had a limited number of images to illustrate their text. The additional notes expand on certain aspects of the text.

1 Vesica piscis geometry in the western tower of Ely Cathedral

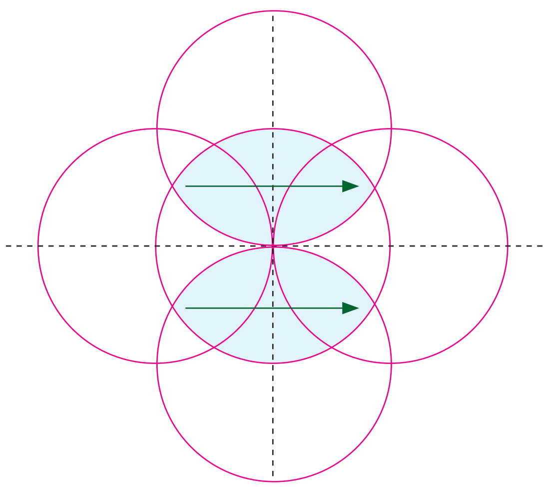
The western tower at Ely Cathedral is square on plan, with all four faces pierced by an arch. The western wall's small arch acts as the entrance and exit to the cathedral; the eastern wall frames a high arch into the nave, the south wall frames an identical high arch into the eastern wing of the cathedral's facade, the north wall has a blocked arch. The generative geometry defining the tower's square plan is the five circle module, drawn as follows ~

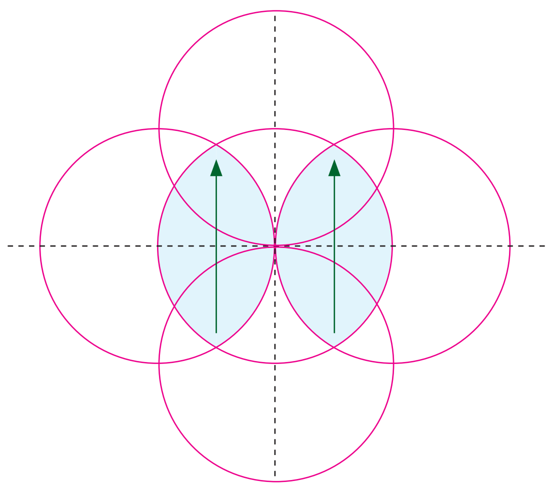




LEFT
Three circles are drawn along a centre line so that each passes through the axis of the neighbouring circle. The three circles intersect at four points, two above and two below the centre line. Arcs drawn from each pair of points intersect at a vertical alignment, perpendicular to the centre line.

RIGHT
The perpendicular cuts the central circle at its north and south poles. Two further circles, drawn from the poles, complete the five circle module. The four outer circles intersect at four points that mark the corners of a perfect square.

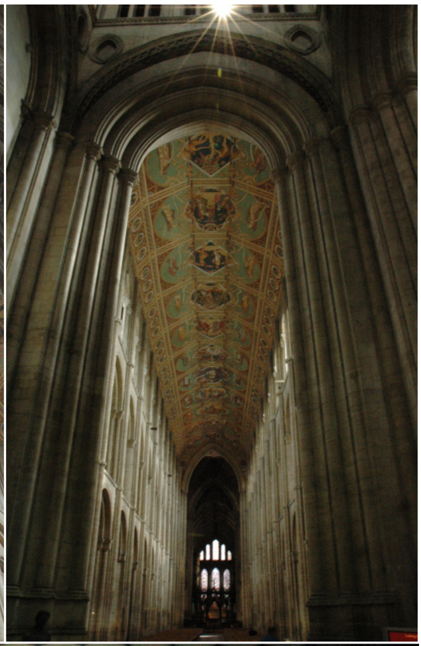




LEFT and RIGHT

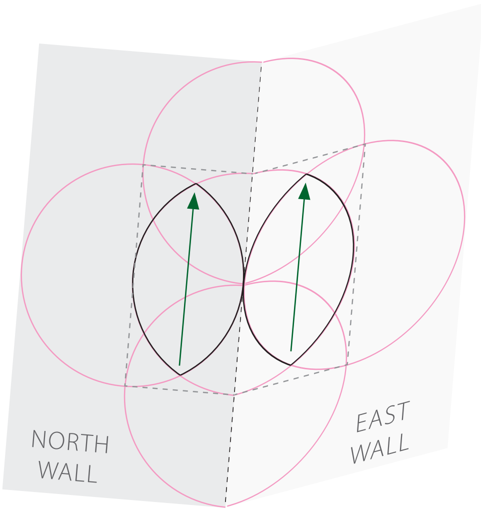
The central circle's circumference and the four compass arcs spanning the circle form two horizontal axis and two vertical axis vesica pisces.

Continued overleaf



TOP LEFT photo
Inside the western tower with the blocked north wall to the left and high eastern arch into the nave to the right.

LOWER photo
The maze occupying the floor of the western tower.



TOP RIGHT photo
The high eastern arch and vista through the nave and choir to the east window.

DRAWING
The double vesica piscis within the five circle geometry of the western tower's floor plan.

Vesicas in the western tower are placed so that those on adjacent walls touch edge to edge at right angles in each of the tower's corners, their placement suggested by the five circle geometry that generates the tower's square floor plan. The geometry can be visualised as drawn on paper or parchment and folded along the vertical centre line to simulate two adjacent walls of the tower.

2 Imperial and metric dimensions

The Imperial system of measurement was the predominant dimensional system used in the design of British historic buildings. The modern practice of converting such dimensions into metric equivalents can obscure the original proportional relationships, or worse, render them incomprehensible. Where Imperial dimensions are simple, and, as with the medieval rod, can often be expressed as fractions, the metric equivalent generates large and unwieldy numbers that are difficult to both memorise or calculate. The medieval rod, at 16½ feet, two thirds of a rod at 11 feet and one third at 5½ feet become 500.3 cm, 335.3 cm and 167.6 cm respectively as metric dimensions, thus losing the simplicity, precision and intelligibility of the Imperial dimensions. Therefore, when measuring historic buildings, Imperial dimensions should be taken to allow the original proportional relationships to be comprehended, and their metric equivalents given alongside.

3 Fractions and compass geometry

Halving the medieval rod (16½ feet) in a diminishing sequence gives 16½, 8¼, 4$^1/_8$, 2$^1/_{16}$ and 1$^1/_{32}$, each fraction being precisely half of the next greater and double the next smaller. This sequence is in accord with the use of compass geometry where a diameter halved gives the circle's radius and a radius doubled gives the circle's diameter. The fractions and the geometry are both mnemonics that are easy to hold in the mind and easy to demonstrate, for example, by halving and apple, quartering the halves, halving the quarters to eighths and so on.

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