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Breaking the Barriers – Accessing the Theoretical Perspectives on the Road to Structure and Form

Abstract

A wide range of geometric principles, concepts and perspectives, invariably sourced in ancient times, offer potential as problem solving tools in the twenty-first century. This appears to be accepted by design teachers and instructors worldwide, but evidence for the wide-spread inclusion and systematic delivery of such material in the design curriculum of the first decade of the twenty-first century is largely lacking. This is surprising, since many of the great breakthroughs in design, and especially architecture, were conditional upon individuals who not only understood materials and processes but also had an intimate knowledge of the geometry of structure and form. Notable examples include William Morris, Louis Foreman Day, Frank Lloyd Wright, Le Corbusier, and Richard Buckminster Fuller. There seems therefore to be a barrier preventing this potentially beneficial development. The authors believe that this barrier is the perceived lack of a clearly understandable and accessible collection of literature of importance to the development of relevant teaching material. This is the problem being addressed by this paper.

Design teachers and instructors perceive themselves at a disadvantage when faced with developing curriculum material relating to structure and form. It is often the case that explanations of key concepts and principles are hidden in relatively obscure literature and wrapped in unfamiliar symbols and terminology. This paper aims to challenge this state of affairs first by identifying relevant literature which is accessible to non-mathematicians, and second by providing an outline from which design educationists, with just a basic knowledge of geometry, may develop an educational module to meet the specific needs of their own students.

A range of topics associated with structure and form in design is introduced. Various regular polygons that are capable of tiling the plane without gap or overlap are identified. Periodic (or repeating) and aperiodic (or non-repeating) tessellations are considered. Inter-related concepts, associated with the Fibonacci series and the golden section, are explained. The nature of the five regular polyhedra (or Platonic solids) and the thirteen semi-regular polyhedra (or Archimedean solids) is explained. Reference is made to principles associated with modularity, and the nature of fractals and scale symmetry is outlined. Sample exercises and examples of student assignment work are presented. Literature appropriate for use by teachers and instructors, involved in developing curriculum material, is identified.

Many of the geometric concepts and ideas introduced can, with insight and vision, offer immense potential as problem-solving design tools in the twenty-first century. The intention of this paper is to stimulate interest among teachers and instructors concerned with design education, and to rekindle their awareness of the fundamental geometric concepts and principles which encroach on the design process. The stress is on providing guidelines which will assist design teachers in the development of a curriculum that fits well with their own teaching needs. As in-house research progresses, this also should feed the curriculum and thus allow its further development.

Key Words: *structure, form, tilings, patterns, polyhedra.*

Introduction

In both two- and three-dimensional design, including textile, graphic, fashion and product design, an awareness of the geometrical concepts and principles underlying design structure and form is of fundamental importance. Many of the geometric concepts and associated principles underlying structure and form in design can be sourced in ancient times and transcend the boundaries between art, science and mathematics. An understanding of these can offer immense potential as problem-solving design tools. This is widely accepted by design teachers and instructors worldwide. Probably the most notable early text, aimed primarily at developing an understanding of structure and form (particularly in the context of biological processes), is *On Growth and Form* by Thompson (1st ed. 1917, and later editions in 1917, 1942, 1961, reprinted several times between 1966 and 1984, and with a seventh printing in 2005). The work of Critchlow (1969) is particularly notable. Recent examples include: Pearce, 1990; Ching, 1996; Ching, 1998; Elam, 2001; Leborg, 2004). A good general textbook covering a wide range of relevant subject areas was provided by Kapraff (2001). Publications such as these have informed research concerned with the geometrical aspects of design, and have inspired developments in the curriculum delivered to students in many higher education institutions. This paper presents details of one such development. Running under the title, 'Design Theory – Structure and Form', this lecture-based course is concerned largely with the geometrical aspects of design, and is delivered as a core module to three-hundred design students (including graphic design, textile design and fashion students) and is selected as an optional module by a further fifty students. The syllabus is based largely on the past or current research interests of the authors of this paper. Assessment of the module is by written assignments plus formal written examination.

The objective of this paper is to present an outline of subject matter of importance to design teachers and instructors who wish to develop the curriculum presented to design students. The intention is to rekindle an awareness of fundamental geometric concepts and principles, regarded as essential components of the design curriculum one hundred years ago, but gradually eased out during the past three or four decades. Two sample exercises which could be developed into more substantial assignment briefs are presented. Key texts are identified, and a few examples of student work are given (Figure 9). The paper should be of particular value to design teachers who are not from a conventional, art and design educational background, but whose current professional duties involve the development of theoretical components to underpin a largely practice-based design curriculum. To others, the paper may act as the basis of a simplistic refresher course, as a source from which to build supplementary teaching material, or as a framework to which current curriculum material could be added. Many experienced professional practitioners will have an intuitive familiarity with the principles mentioned here, and may well be pleased or intrigued at their formalisation in an academic setting.

The wider spectrum of geometric analysis was considered in an interesting article by Reynolds (2001). Various geometric characteristics, principles, concepts, constructions, comparative measures and ratios are of particular importance to both the design practitioner and the design analyst. These include the following:

- 1:1 (square).
- π: radius (circle).
- Square root series √2 (=1.4142): 1; √3 (=1.732): 1; √4 (=2): 1 etc.
- Regular polygons (particularly squares, pentagons and hexagons), Reauleaux polygons, the ad quadratum, the vesica pisces, the sacred cut and other constructions.
- The golden section, Phi (ϕ) or 1.618:1 and various associated constructions such as the golden rectangle or golden spiral.
- Triangles (equilateral, isosceles, right angle, scalene).
- Lattice structures (including Bravais lattices) and grids based on the Platonic, Archimedean or other sorts of tilings.
- Various musical series, including 1:1; 1:2; 2:3; 3:4, etc.

- Geometric symmetry and its component geometric operations (or symmetries).

It is recognised that all of the above are of value in the armoury of both the practitioner and the analyst. However, this paper focuses on only a few of these, and is by no means all encompassing. It simply identifies some of the more important theoretical aspects of structure and form, which have been included in the curriculum at the authors' educational institution, and which have been considered (by students) to be important tools in addressing the requirements of many practice-based assignments. Meanwhile, tutors have remarked on qualitative improvements in the responses to these assignments based, at least in part, on the inclusion of the curriculum material presented in summary form in this paper.

Point, line, shape and form

Several inter-related structural elements are of importance in the design process. These include: point, line, shape or form, and pattern. Point is the basic graphic element from which all visual expression springs. A collection of connected points (or a moving point) constitutes a line. Lines have psychological impact, influenced by their direction or orientation, weight and emphasis, and variations in these. Lines may be human-made or may be created by nature. They may exist by implication (as an outline between two colours or two textures, for example) and may be orientated horizontally, vertically or diagonally. They may be straight or curved. Together, lines constitute forms and shapes, and create areas or masses which define objects in space. The word "shape" is best used to express length and width in two-dimensions, and the word "form" to express length, width and depth in three dimensions. For definition and discussion of the nature of point, line and form, as well as other elements of a "visual grammar", it is worth referring to Leborg (2006). Lidwell et al (2003) presented a well produced and well illustrated introductory text which dealt with a wide range of geometric and other concepts of importance to designers.

Polygons, circles and other constructions

Polygons are enclosed figures with sides (represented, for example, by lines on paper). Regular polygons have equal sides and equal angles. The names attributed to regular polygons have their origin in Greek: a pentagon with five sides, a hexagon with six sides, a heptagon with seven sides, an octagon with eight sides, a nonagon with nine sides and a decagon with ten sides. Students should familiarise themselves with the construction of both a regular pentagon and a regular hexagon. A circle may be considered as an infinite-sided polygon, without beginning or end. It is the easiest geometric figure to construct with accuracy and, over the years, has had a multitude of uses in the visual arts. Amongst much else, it is associated with rainbows, halos, the prayer wheel, the marriage ring, rose windows in European mediaeval cathedrals and pre-historic stone circles. It is a vital component in geometric construction and the discipline of geometry would have a limited range without it. Lawlor (1982) provided a useful review of various geometrical constructions. Reuleaux polygons, named after the German engineer Franz Reuleaux (1829-1905), have curved rather than straight sides (similar to the British 20 and 50 pence pieces). They have an odd number of sides and each side is comprised of an arc with a centre at the opposite angle. An important characteristic is that such constructions have a resultant centre equidistant from any point on any side. Examples are given in Figure 1. Analysis of buildings at Pompeii and Herculaneum suggests that the design of many ancient Roman houses was based on systems of proportion associated with the square. Two particular systems of proportion are of importance: the so-called "ad quadratum" and the "sacred cut".

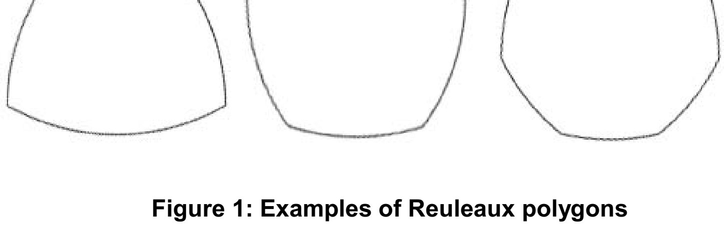

Figure 1: Examples of Reuleaux polygons

Regular and semi-regular tilings

The term “tilings” is used when referring to polygons which cover (or tessellate) the plane, edge-to-edge, without gap or overlap. A regular tiling (or tessellation) is comprised of copies of a single polygon of the same size and shape. Tessellations have been traced back to ancient cultures, but their formal study (in the academic sense) is relatively recent. Johannes Kepler (1571 – 1630) conducted an early study of tessellations in 1619, and produced a notable attempt to tile the plane using figures with five-fold rotational symmetry. Major scientific progress came in 1891 when Federov, the Russian crystallographer, proved that every regular tiling of the plane is constructed in accordance with one of seventeen combinations, the same combinations of importance to pattern construction. Grunbaum and Shephard in their monumental treatise *Tilings and Patterns*, published in 1987, charted much of what is currently known about the mathematics of tilings. Only three regular polygons tessellate the two-dimensional plane: equilateral triangles, squares and hexagons. Tessellation is only possible where angles at the vertex (i.e. where the angles meet) add up to precisely 360 degrees. The three possibilities, each using one type of regular polygon, are known as the Platonic or regular tilings. Several forms of notation are in use. For example a tiling may be notated by choosing a vertex and counting the sides of the polygon which touches it as well as the number of polygons involved at the vertex. In the case of the hexagon tiling, each polygon has six sides and three of these polygons meet at each vertex; an appropriate notation is {6, 3}. Using this system, the other regular tilings can be notated by {4, 4} and {3, 6}. Illustrations for each of the three tilings are presented in Figure 2.

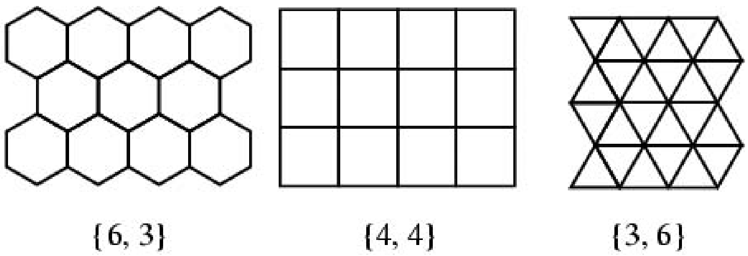

Figure 2: The three regular or Platonic tilings

Tessellations of the plane, using two or more regular polygons, are also possible. There are eight possibilities, and these are known as the Archimedean or semi-regular tilings (Figure 3). A rule is that each vertex must be identical. An interesting review of the nature of Islamic tilings was given by Critchlow (1976, reprinted 2004).

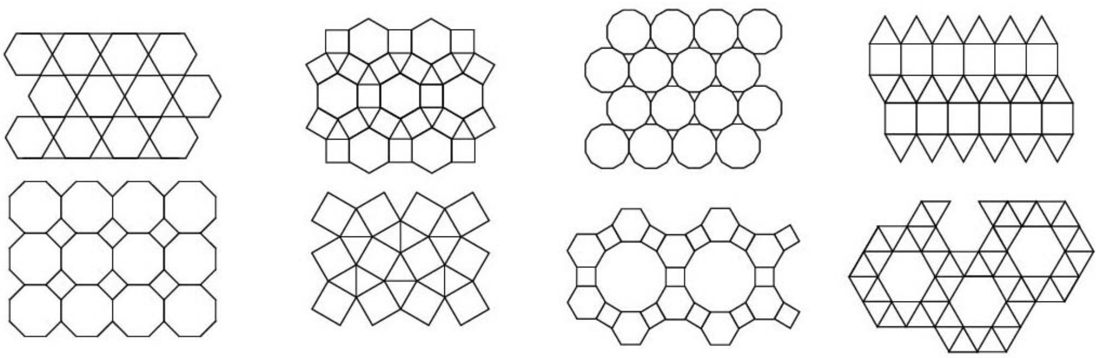

Figure 3: The eight semi-regular or Archimedean tilings

Motifs, patterns and symmetry

Motifs are the building blocks of patterns. The principal characteristic of a regular repeating pattern is the repetition of a motif by a given distance across the plane. Patterns are considered to have symmetry characteristics. In this case, the meaning of the term “symmetry” extends beyond its common every-day usage to cover geometric actions beyond bi-lateral symmetry. Patterns may exhibit one or more of four symmetry operations or symmetries. These are: translation, by which a motif undergoes repetition vertically, horizontally, or diagonally at regular intervals while retaining the same orientation; rotation, by which a motif undergoes repetition round an imaginary fixed point; reflection, by which a motif undergoes repetition across an imaginary line, known as a reflection axis; glide-reflection, by which a figure is repeated in one action through a combination of translation and reflection, in association with a glide-reflection axis. Schematic illustrations of the four symmetry operations are presented in Figure 4. Patterns may be classified with respect to their symmetry characteristics. Combinations of the four symmetry operations yield seventeen possibilities (or classes). An explanation of fundamental concepts was given by Hann and Thomson (1992), Hann (2003), Stevens (1984), and Washburn and Crowe (1988 and 2004). A useful text from which to develop an understanding of symmetry in tilings was provided by Schattschneider (1990). Although designers working in two dimensions often acknowledge the importance of geometry in the construction of regular patterns, they invariably hesitate to leap beyond tried and tested repeat structures (based largely on block or half drop repeats). This reticence is understandable, since the bulk of literature concerned with two-dimensional design geometry is often inaccessible due to the preponderance of unfamiliar terminology. An appreciation of symmetry concepts can help designers to make that leap into using novel repeat structures. Probably the best sources to aid the construction of regular repeating patterns are Schattschneider (1990), Stevens (1984) and Horne (2000).

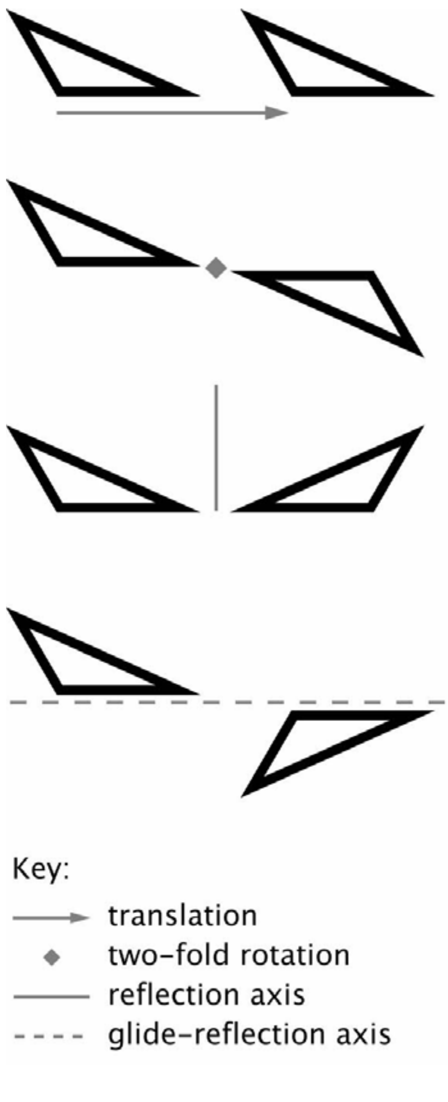

Figure 4: The four symmetry operations

Aperiodic tilings

The regular and semi-regular tilings, mentioned above, translate (or repeat) in two distinct directions across the plane without gap or overlap. These may also be referred to as periodic tilings or tessellations. There is also a class of tilings which do not translate, but nevertheless cover the plane without gap or overlap. These are termed non-periodic or aperiodic. During the latter part of the twentieth century, the British mathematician Roger Penrose developed an aperiodic tiling, which exhibited five-fold rotational symmetry, at various points within its non-repeating structure. The tiling is comprised of two rhombi (known as kites and darts), one with angles of 36 and 144 degrees and one with angles of 72 and 108 degrees. In constructing the tiling it is necessary to adhere to a series of rules specified by Penrose (1990). In the context of Penrose tilings, it is of interest (and probably also of significance) to note that the quantity of one rhombus used in the construction relative to the other conforms to a ratio of 1.618. This ratio is closely associated with the so-called golden section or a numerical series known as the Fibonacci series. The nature of the Fibonacci series and the golden section is dealt with the section below. A Penrose-type tiling is shown in Figure 5.

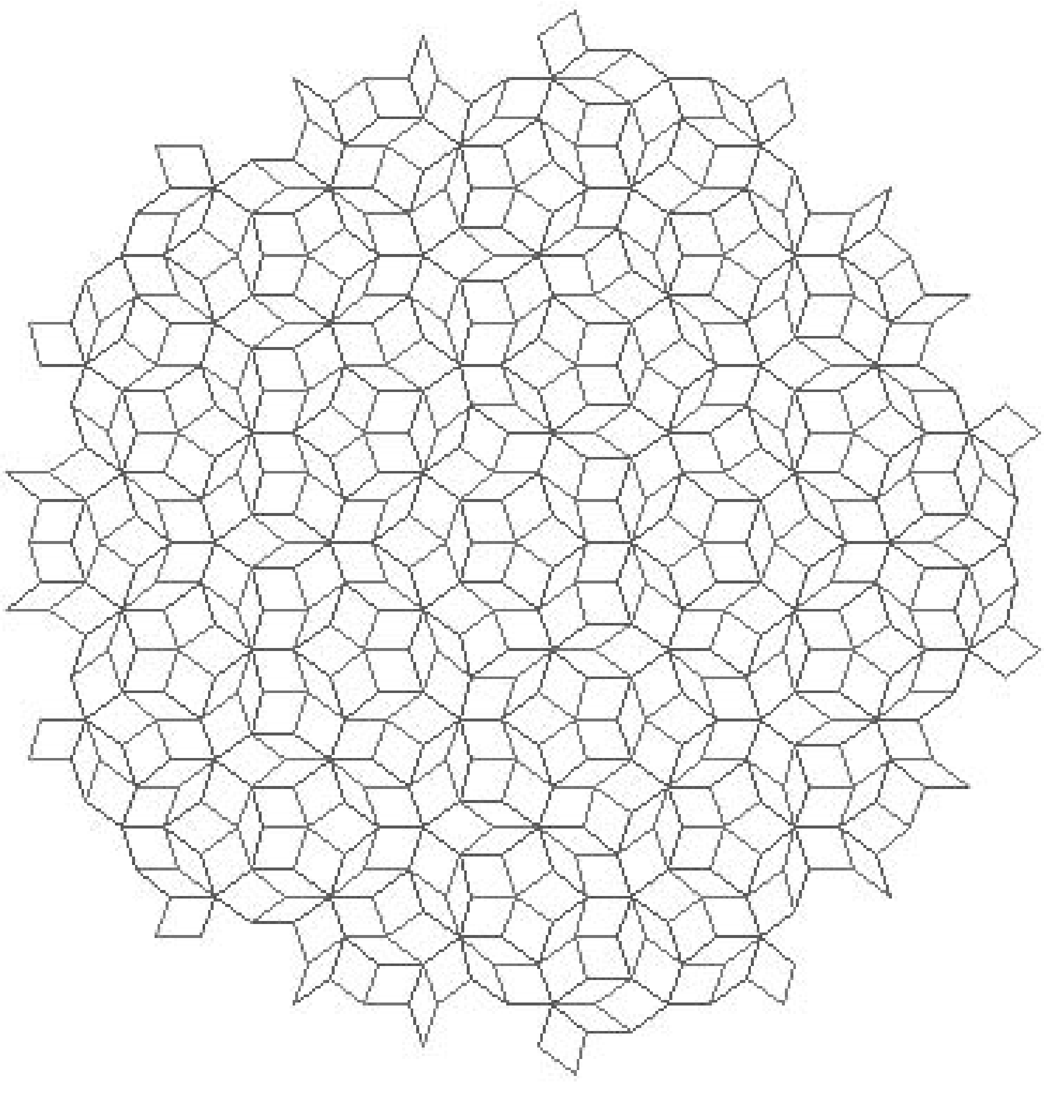

Figure 5: A Penrose-type tiling

Polyhedra

A polyhedron is a solid consisting of polygonal faces. These faces meet at edges, and the edges meet at vertices (singular vertex). There are five regular polyhedra (known as the "Platonic solids") each comprised of combinations of one specific type of regular polygon (Figure 6). With each Platonic solid, the faces are thus identical in size and shape, and the same number of faces meets at each vertex. The five Platonic solids are as follows: the tetrahedron (four faces), the cube or hexahedron (six faces), the octahedron (eight faces), the dodecahedron (twelve faces) and the icosahedron (twenty faces). The difficulties encountered in attempting to apply two-dimensional repeating designs to regular polyhedra, avoiding gap and overlap and ensuring precise registration, are a particular research focus currently at the authors' educational institution. The symmetry characteristics of importance to the process have been identified, and the rules which affect the patterning of each of the five Platonic solids are being developed. These will ultimately be refined, applied and the associated concepts integrated/imported into the curriculum described in this paper.

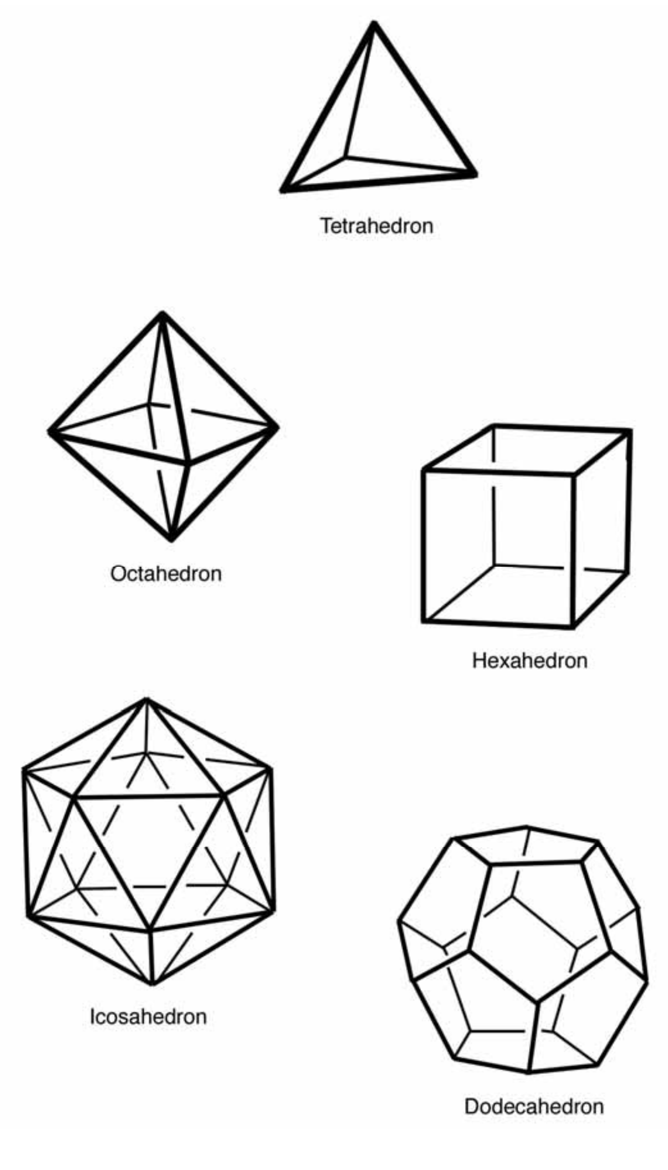

Figure 6: The five Platonic solids

A further set of polyhedra (thirteen in total) can be obtained largely from the Platonic solids by cutting away the corners and producing “truncated polyhedra. These are known as the “Archimedean solids”, and each is formed from combinations of two or more types of regular polygonal faces (Figure 7). They are considered “semi-regular” and, in each case, the vertices are identical. A good explanatory text was provided by Cromwell (1999).

Probably the best known of these thirteen solids is the truncated icosahedron (similar in shape to a soccer ball, with 30 faces comprised of 20 regular hexagons and 12 regular pentagons). It is worth remarking that a highly significant scientific advance, reported in 1985, was the discovery of a super-stable all-carbon C60 molecule, arranged in the form of a truncated icosahedron. The molecule was appropriately named Buckminsterfullerene (after the architect Buckminster Fuller whose ideas had stimulated the quest for such structures). C60 Buckminsterfullerene is a form of carbon alongside diamond and graphic. Its physical properties, and thus its ultimate performance, are readily attributable to its geometric form, a common relationship evident across many areas of material science and engineering and an attribute which should offer no surprise to designers.

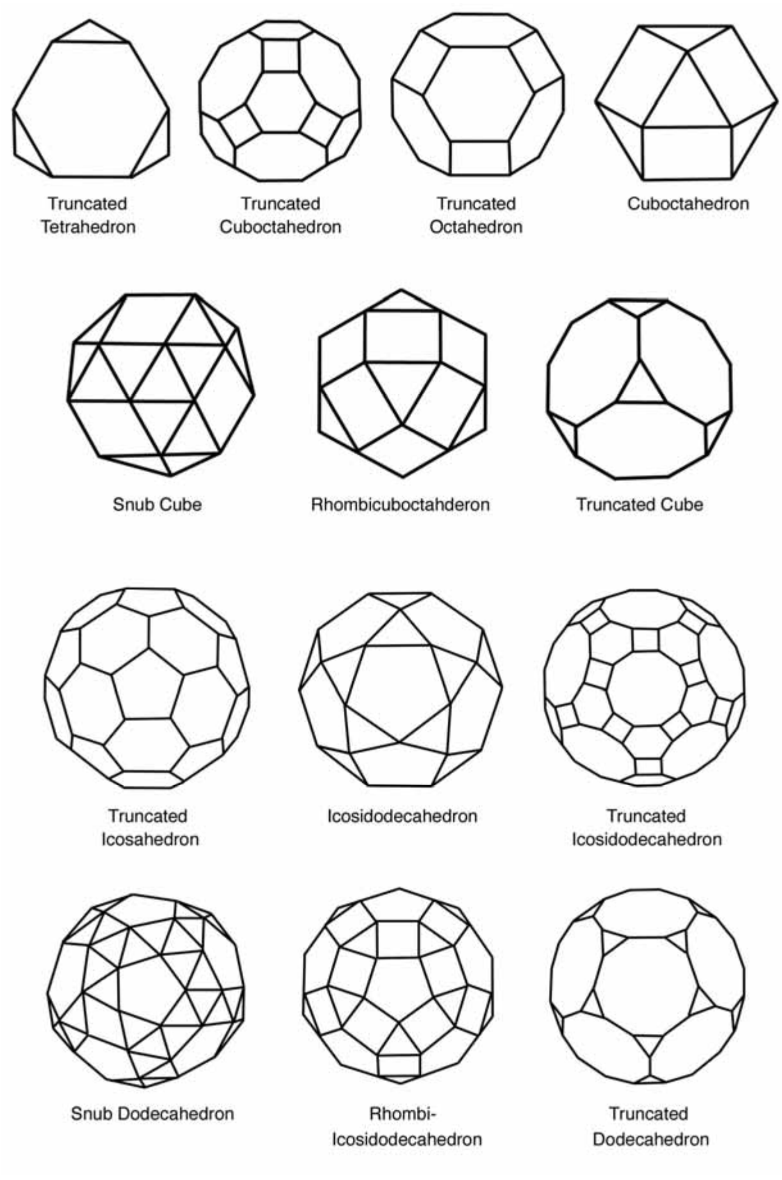

Figure 7: The thirteen Archimedean solids

Fractals and self-similarity (or scale symmetry)

A fractal is a geometrical shape made up of identical parts each of which is (at least approximately) a reduced/size copy of the whole. Fractal, from the Latin fractus meaning fractured or broken, refers to a unique type of geometric shape. Fractals have two distinct properties: they tend to exhibit infinite detail and they conform to the same shape at different scales, a property known as self-similarity. Fractals can be based on mathematical models, but are also common in real life. Examples of nature's fractals are clouds, coastlines, lightning, various vegetables (e.g. cauliflower and broccoli) and mountains. This phenomenon of self similarity, or scale symmetry, is exhibited in the Koch snowflake shown in Figure 8. The basic unit of the Koch snowflake, first constructed by the mathematician Helge von Koch (1870-1924), is the equilateral triangle which can be built up into a much larger structure while retaining certain similarities at the smaller scale level. Although the roots of fractal geometry can be traced to the late 19th century, it was the work of Benoit Mandelbrot, in the 1960s and 1970s that popularized the concepts. His 1961 study of similarities in large- and small-scale fluctuations of the stock market was followed by work on the turbulent motion of fluids and the distribution of galaxies in the universe. A 1967 paper on the length of the English coast showed that irregular shorelines are fractals whose lengths increase with increasing degree of measurable detail. By 1975, Mandelbrot had developed a theory of fractals, and publications by him and others made fractal geometry accessible to a wider audience.

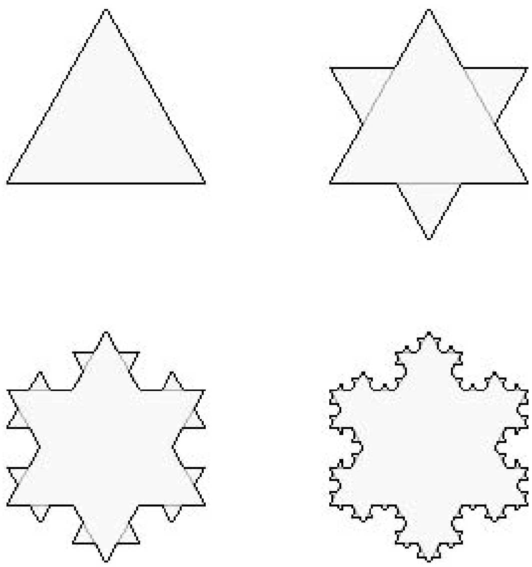

Figure 8: The Koch snowflake

Modularity

Modularity embraces the concept of "minimum inventory and maximum diversity". In other words, from a few basic modules (such as two or three tile shapes), a large collection of different structures (or solutions) is possible. The concept is of relevance to science, art and design, and can be detected throughout the natural world. It offers potential for innovation in the decorative arts and design, and is common in two-dimensional repeating patterns as well as architecture. A comprehensive account is given by Pearce (1990). Figure 9 shows twelve modular designs created by tessellating tiles cut from an equilateral triangle and a hexagon (following the specifications given in Exercise 2 in the Appendix).

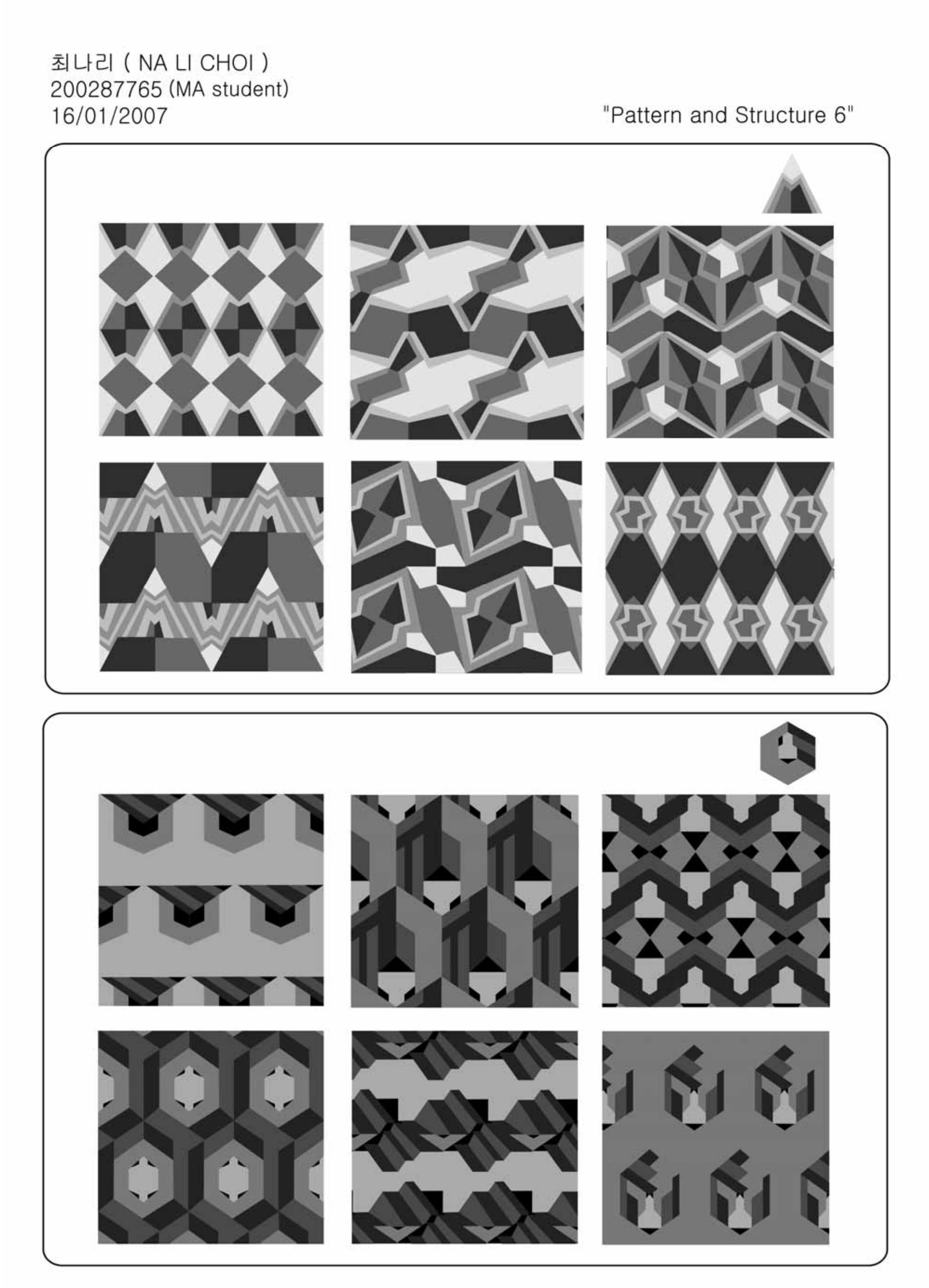

Figure 9: Modular designs based on specification given in Exercise 2 (Appendix)

The Fibonacci series and the golden section

A special series of numbers (1, 1, 2, 3, 5, 8, 13, 21, 34, 55…..) was discovered by Leonardo Fibonacci in 1202 CE as a result of an investigation of population growth among rabbits. It was found that the proportion yielded by successive numbers within the series approximated to 1.618, which has become known as Phi. The proportion was known to the ancient Greeks as the "golden section". Phi can be derived in many ways and shows up in relationships throughout the natural, constructed and manufactured worlds and beyond. It can be detected in architectural contexts, is associated with proportions of the human body, other animals, plants, DNA, the solar system, music, dance, sculpture and other art forms. Both the Greeks and the ancient Egyptians are believed to have used the golden section when designing their buildings and monuments. The proportion is evident in the works of various artists; Leonardo da Vinci and George Seurat are contrasting examples. The architect, Charles-Edouard Jeanneret (known as "Le Corbusier") developed a rule of design known as the "modular", a measure related to the proportions of the human body. The associated numerical series conformed closely to Fibonacci numbers.

Rectangles, triangles and spirals, which conform to golden section proportions, can be constructed. Students should develop expertise in drawing these. Both Huntley (1970) and Ghyka (1977ed.) gave useful guidelines. Golden section proportions and bi-lateral symmetry have been associated (separately) with attractiveness in human beings, particularly in the context of facial features. An interesting review article dealing with the golden section was produced by Green (1995). A good account of Fibonacci numbers was given by Dunlap (1997).

In conclusion

The value of geometry in the art and design curriculum was recognised during the nineteenth and early twentieth centuries. Today, worldwide, in both developed and developing economies, it appears that the priority in design education is on training students in the usage of the most recent software, often at the expense of providing an understanding of more fundamental theoretical issues. Geometric concepts and principles are of importance to the success of all two- and three-dimensional design and should thus form an important element of the curriculum in all design courses. The reticence of instructors and teachers to address this issue is understandable, for often the knowledge and understanding required to develop appropriate theoretical curricula is hidden in relatively obscure literature, and wrapped in unfamiliar symbols and terminology. This paper provides a basic outline from which design educationists, with just a basic knowledge of geometry, may develop a module to meet the specific needs of their students. Effective teaching at university level should be conducted in a climate of research. As in-house research progresses this should feed the curriculum. A syllabus should not be set but should be in a state of development from year to year. Meanwhile students, on gaining a basic understanding of the geometrical concepts and constructions identified in this paper, should be able to conduct structural analyses of naturally occurring phenomena, human-made objects, images, paintings, sculpture, patterns, tilings and other forms of two- and three-dimensional designs. Two sample assignments, of the type set at the authors' educational institution, are presented in the Appendix. These may be developed further into more substantial assignments. Where possible, assignments such as these should be integrated with conventional studio-based activity.

Acknowledgements

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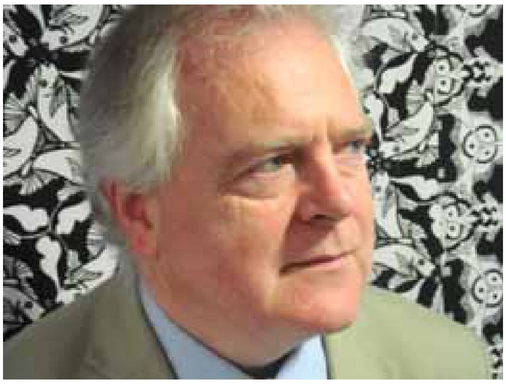
Appendix

Exercise 1: Symmetry and proportion
Select a frontal photograph of a human face that you consider to be very attractive. You are required to conduct a geometrical analysis of this image, with the objective of establishing the degree of bilateral symmetry and the presence of proportions/ratios which conform to the Fibonacci series and the associated golden section. You may wish to conduct the following measures: top of head to tip of chin; centre of mouth to tip of chin; centre of mouth to tip of nose; tip of nose to bridge of nose; bridge of nose to ear; bridge of nose to pupil of eye; pupil to pupil; width of nose at outer part of nostrils; pupil to eyelash; eyelash to eyebrow; eyebrow to eyebrow; any other measure you believe to be appropriate. You may then wish to establish if there are any apparent relationships between these measures. You may wish also to draw a mid-way line, down the centre of the image, and to measure features to the right and left of this line. Once measurements and calculations have been completed, you are required to present you data in tabulated form, and to briefly discuss the significance of your findings.

Exercise 2: Modularity and pattern construction
You are required to produce a collection of repeating designs, each created from tiling elements cut or drawn from a regular polygon (six designs from elements of a square, six designs from elements of an equilateral triangle and six designs from elements of a hexagon). To begin, draw a square to dimensions of your choice. Cut into two or more unequal parts. You have thus produced two or more tiles of different dimensions. Colour each tile with a colour of your choice. Make multiple copies (by

scanning or photocopying each coloured tile). Use these two or more different shaped tiles (in any numerical proportion you wish) to create a collection of six periodic tilings, which cover the plane without gap or overlap. A minimum of four repeats of each design must be shown. Each design must be original, precisely drawn, and distinctly different, and must not relay solely on a change of scale as a means of differentiation. Feel free to use computing software of your choice. Repeat the process using a regular hexagon and an equilateral triangle.

CURRICULUM VITAE



Professor M. A. Hann is a graduate three-times over (BA, MPhil and PhD) from the University of Leeds and has held an academic position at Leeds since 1980. He was promoted to Senior Lecturer (1991) and to Reader in International Textile Design (1997). He is a Chartered Textile Technologist and was elected to Fellowship of the Textile Institute in 1991. He is Director of the University of Leeds International Textiles Archive (ULITA) and holds the Chair of Design Theory at Leeds. He has lectured in historic and contemporary world textiles for around twenty years, and has collected textiles throughout much of south and south-east Asia. Publications include ten monographs or catalogues; five chapters to books; around fifty refereed contributions to scholarly journals; two films produced, directed and edited; twelve exhibitions curated; thirty-three conference presentations (mainly international conferences and mainly as an invited or key note speaker). He is an experienced researcher and has supervised over 100 undergraduate and postgraduate student projects including around forty Masters dissertations and twelve PhD theses. Research interests cover the historic, cultural and economic aspects of textile production and patterning worldwide, with expertise concerning innovations in linen manufacture, resist dyeing and printing, decorative weaving, aspects of textile archiving, conservation, documentation and exhibition as well as the geometry of two-dimensional design, especially repeating patterns.