
Preface and Acknowledgements

More than with any other cultural heritage, the work of Muslim artists over the centuries reveals the visual beauty that is inherent to geometry. Drawing inspiration from geometry led to an abundance of aesthetic innovations within the tradition of Islamic geometric design that were inexorably associated with methodological practices. Of particular importance was the discovery that geometric patterns could be extracted from underlying polygonal tessellations, herein referred to as the *polygonal technique*. Over time, and in the hands of skilled and dedicated practitioners, this design methodology engendered the extraordinary breadth of diversity that characterizes this artistic tradition. As architectural ornament, Quranic illumination, and its more limited use within the applied arts, geometric designs were enthusiastically embraced by succeeding Muslim cultures, and along with calligraphy and the floral idiom, became an integral aspect of Islamic aesthetics. As such, its role within Islamic art as a whole is paramount. Yet scholarship of this vast subject remains underrepresented in two key areas: historical development and design methodology. Related to this relative lack of attention is the surprising absence of a comprehensive approach to categorizing the range of patterns within this tradition. Additionally, while the exceptional achievements of past geometric artists serve as a source of inspiration for many contemporary artists, designers, craftspeople, and architects, the loss of methodological knowledge associated with this artistic tradition has substantially thwarted those with an interest in incorporating such designs into their work. In consideration of these gaps this book has several intentions: to provide a greater understanding of the developmental history of this remarkable artistic tradition; to emphasize a more nuanced attribution of the geometric and design diversity that is a hallmark of this distinctive form of art; and to provide a detailed elucidation of the methodological practices that are responsible for the diversity, beauty, and longevity of this artistic discipline. What is more, it is my hope that the focus upon design methodology, including the use of computer algorithms, will empower those with a sincere and dedicated interest in applying the creative processes of the past to their own original works.

The combined focus upon historical development and design methodology within this work requires an approach to the subject of Islamic geometric patterns that is both chronological and analytical. As such, there is an inevitable repetition of information concerning geometric characteristics and the dates and location of specific examples when bridging between these two approaches. This is necessary to clarify historical, geometric, and methodological context throughout the book, and I request the reader's patience and indulgence when encountering such repetition. As a practical consideration, all dates accord with the Gregorian calendar rather than either the Islamic or Persian calendars. In organizing the terminology employed throughout this work I have erred on the side of clarity and simplicity and have generally tried to avoid being overly technical. Wherever applicable, unless there is a compelling reason to do otherwise, I have adopted prior terminology. The glossary provides brief definitions of many of the terms used throughout this work, including those that are of foreign origin (Arabic, Persian, Urdu, Turkish, or Spanish), those that are technical and associated with the science of tiling and geometry, and those that pertain specifically to design methodology. In this latter category, much of the nomenclature is of my own invention. This is due to the fact that many

significant features of this artistic discipline have not been previously identified as such and are therefore without name or title. I argue that the *polygonal technique* was the principle design methodology employed by Muslim geometric artists. This technique has been referred to variously as the *Hankin method* (in deference to Ernest Hanbury Hankin who first identified the historical use of this methodology), or the *PIC method* (polygons-in-contact). I prefer the term *polygonal technique* for its simplicity and descriptive accuracy. In previous publications I have referred to the polygonal mechanism that characterizes the polygonal technique as *subgrids*. However, in the interests of descriptive clarity, in this book I refer to this important methodological feature as the *underlying generative tessellation*, or alternatively as the *underlying polygonal tessellation*. The polygonal technique was employed in two very different modalities: systematically and nonsystematically. My identification of patterns as being either *systematic* or *nonsystematic* results from there being no such previous differentiation by prior scholars. My descriptive titles for the five historical design systems that employ repetitive modules to create geometric designs stem from their not having been identified as systems, *per se*, by other specialists prior to my work. I have titled these as the *system of regular polygons*, the *fourfold system A*, the *fourfold system B*, the *fivefold system*, and the *sevenfold system*. My classification of the four historical varieties of dual-level design has changed slightly from my 2003 account of this discipline (in which I had only identified three types) and results from there being no previous differentiation within the published literature. Rather than employing a descriptive title I have simply used the more prosaic terms *Type A*, *Type B*, *Type C*, and *Type D*. Similarly, my names for the four principle pattern families that are ubiquitous to this tradition stem from the absence of prior identifying classifications from previous sources in the English language. These are descriptively named the *acute*, *median*, *obtuse*, and *two-point* pattern families. In writing about a tradition that encompasses many distinct cultures with separate languages and artistic terms, I have chosen to refrain from employing terms that are specific to select Muslim cultures in writing about this discipline more generally. For example, despite being in common usage, I do not use the Farsi word *girih*, meaning “knot,” when referring to geometric designs. I have sought to keep my geometric terminology as nontechnical as possible, while following convention to maintain clarity. For the most part my terminology corresponds with Craig Kaplan’s in Chap. 4. He prefers the term *translational unit* for what I typically refer to as *repeat unit*. Similarly, he employs the phrase *template tiling* for what I refer to as the *underlying generative tessellation*, or alternatively as the *underlying polygonal tessellation*.

Chapter 1 chronicles the historical development of Islamic geometric patterns from initial influences and early manifestations through to full maturity. In identifying broad stylistic trends, geometric characteristics, and diverse varieties of design, I have referenced multiple individual pattern examples from successive Muslim cultures. My choice of examples reflects the chronological development from simplicity to complexity and will frequently build upon the familiar to introduce the less well known. This choice of historical examples cannot help but be subjective, but every attempt has been made in aligning my aesthetic preferences and value judgments with impartial historical significance. Similarly, the many photographs included within this chapter provide a sense of the broad aesthetic diversity contained within this tradition. In discussing the contributions of successive Muslim dynasties, the general structure within each section flows from the more basic patterns to more complex designs. Emphasis is always placed upon innovations that occurred during a given epoch, as these were primary vehicles for the advancement of this ornamental tradition. Considerable attention is given to the development of dual-level designs with self-similar characteristics. This was the last great outpouring of creative innovation, and despite the relatively small number of examples, their beauty and geometric ingenuity place them into a highly significant category of their own. Attention is also given to the application of geometric patterns to non-Euclidean surfaces of domes and domical niche hoods. There are two varieties of this form of Islamic geometric ornament: those that utilize radial gore segments as their repetitive schema and

those that employ polyhedra as their repetitive device. The latter are far less common, and almost all of the significant historical examples are included within this study. To a very limited extent, each new dynasty is placed into a brief historical context that primarily describes their rise to power, and what set them apart from their predecessors. This will be redundant to historians, but many readers may benefit from the placement of the geometric idiom within a broader cultural and political milieu—however briefly outlined. Attention has been given to the relatively few examples of Islamic geometric design that were created for non-Muslim clients and in some cases by non-Muslim artists. The influence of Islamic art upon non-Muslim cultures is beyond the scope of this study, but the examples cited are worthy of inclusion due to their geometric character as well as their historical circumstance. This opening chapter tracks the history of Islamic geometric patterns through to achieving full maturity and for the most part leaves the later, more derivative manifestation of this tradition for future consideration.

Chapter 2 explores the varied discrete features that characterize this multifaceted discipline. Previous works have concentrated primarily on the variety of star types and regular polygons within specific patterns when categorizing geometric designs, and more recent studies have classified patterns according to their crystallographic plane symmetry group. Yet there are many more distinguishing characteristics that help to broaden an overall understanding and appreciation of this artistic tradition. Emphasis is given to the variety of repetitive stratagems employed by Muslim geometric artists. Of course the simple square, equilateral triangle, and regular hexagon were commonly employed as repeat units, and many very complex patterns employ these well understood structures. From as early as the eleventh century patterns with alternative repetitive structures entered the artist's repertoire. These included rectangular, rhombic, and irregular hexagonal repeats, as well as designs with rotational symmetry. The repetitive stratagems included in this chapter also include *oscillating square* designs and *rotating kite* designs. These are essentially orthogonal, but by incorporating alternating rhombi and squares in the former, and alternating kites and squares in the latter, it is possible to produce designs with seemingly incompatible regions of n -fold local symmetry into an otherwise fourfold structure. Considering the early period of origin, and the fact that there was no historical precedent that these Muslim geometric artists could have borrowed from, their familiarity with these diverse repetitive structures is surprisingly sophisticated and predates analogous repetitive structures from other cultures by many centuries. The intrinsic relationship between the n -fold symmetry of a given pattern and the proportions of its repeat unit are examined in detail. As patterns became increasingly complex, with multiple regions of local symmetry incorporated into a pattern matrix that was based on neither a square nor a triangular repeat, these regions of local symmetry were critical proportional determinants of the overall repetitive structure: be it rectangular, rhombic, or irregular hexagonal. This chapter also differentiates between patterns according to their numeric qualities and postulates an abbreviated descriptive nomenclature that is based upon rather basic geometric and numeric analysis. In discussing Islamic geometric patterns it is sometimes difficult to express concisely and with precision the qualities of a given pattern. This is especially true of the more complex designs. The approach to identifying the salient features of a given design that is advocated in this chapter is intended to promote both cogency in dialogue and clarity in understanding. Once again, this section moves from the simple to the complex, beginning with examples that employ single star forms or regular polygons into simple orthogonal or isometric repetitive structures, and ending with complex designs with multiple star forms within a single pattern matrix that repeat upon the less common grids mentioned above. In classifying these more complex structures, I have identified the conventions for including added regions of local n -fold symmetry of the primary stars. These are placed at key locations within the repetitive structure, such as the vertices of the repetitive grid, the vertices of the dual grid, upon the midpoints of the repetitive edges, and occasionally upon lines of radius within the field of the pattern matrix. Another category of

design that is examined imposes a geometric motif into a repetitive grid that is typically incompatible with the symmetry of the motif: for example, the placement of octagons into an isometric structure. Muslim geometric artists produced many fine *imposed symmetry* patterns, and this variety of design has been largely ignored in previous studies. Classification according to the crystallographic plane symmetry group is critical to understanding the geometric underpinnings of this tradition. There are just 17 ways in which translation, rotation, reflection, and glide reflection dictate the repetitive covering of the two-dimensional plane. Other than those that have either rotational symmetry or cover a non-Euclidean surface, all historical Islamic geometric patterns adhere to one or another of these 17 plane symmetry groups. This section focuses primarily on the geometric characteristics of the plane symmetry groups as manifest within the Islamic geometric idiom, and only slight reference is made to the relative occurrence of different symmetry groups within this overall tradition. This work does not include a statistical analysis whereby individual designs from individual Muslim cultures provide the data points for determining shifting preferences for specific symmetry groups throughout the history of this artistic tradition. Such anthropological and ethnographical studies have been highly revealing of the artistry of other cultures, such as the textile arts of the Americas,¹ but as pertains to Muslim geometric art, this remains the work of future scholarship.

Perhaps the least apparent and least understood classification within the tradition of Islamic geometric pattern concerns design methodology. Considerable attention is given to this subject throughout this book. Historical examples of Islamic geometric art are reflective of multiple disparate forces all of which combine to create a given piece, be it an architectural panel or Quranic illumination. This influential confluence includes the aesthetic predilections of the specific cultural milieu, the personal preferences and aesthetic judgments of the artist balanced with the wishes of the patron or client, the technical and material constraints of the medium, and the stylistic impact of design methodology. Less complex patterns from this design discipline can often be created with more than a single methodology. However, as patterns increase in complexity, the formative method employed in their creation has a pronounced stylistic influence upon their aesthetic nature. The question of methodology is somewhat thorny in that there is surprisingly little historical evidence, and there are several competing theories as to the specific methodology that is most relevant to this tradition. I am a proponent of the polygonal technique as the design methodology that is most responsible for the tremendous diversity and complexity that are hallmarks of this form of art. I have come to this conclusion based upon several criteria: the preponderance of historical evidence from several sources, including Quranic manuscript illuminations, design scrolls (most notably the Topkapi scroll), and multiple architectural representations; the fact that the polygonal technique readily allows for the production of the four pattern families that are fundamental to this tradition; and the fact that only the polygonal technique is suitable for producing the plethora of especially complex patterns found in this tradition. The section of Chap. 2 that pertains to differentiation between design methodologies begins with the polygonal technique and discusses the historical evidence in considerable detail. This section also examines the key features that result from the employment of the polygonal technique, including the distinctive features of the four pattern families, and how they are the product of different types of pattern line application to the underlying generative tessellations; the systematic use of the polygonal technique in developing the five historical design systems—each with its own distinctive aesthetic merit; and the nonsystematic use of the polygonal technique wherein the connective polygons in each underlying generative tessellation are distinct unto themselves and will not recombine into other tessellations. This section on the polygonal technique also focuses on *additive patterns*, a method of increasing the complexity of otherwise less complex patterns that was especially popular, but by no means exclusive to the Ilkhanid dynasty of Persia.

¹ Washburn and Crowe 1988 and 2004.

The design methodology that has been promoted most widely to date as being primarily responsible for Islamic geometric patterns is referred to herein as *point-joining*. Multiple books by numerous authors have advocated for this method of creating patterns, but unless I am very much mistaken, none have given it a name *per se*. This methodology involves setting up a repetitive cell (such as a square), with a matrix of internal lines and circles that provide coordinate points that can be joined with lines that produce a pattern: hence the descriptive name *point-joining*. This technique has the benefit of producing patterns precisely and quickly at whatever scale is required. However, there are several significant problems with this methodological approach. From a practical perspective, point-joining has three main problems: (1) it does not lend itself to creating original designs, but is primarily useful in recreating existing patterns in a step-by-step fashion; (2) it is impractical for recreating complex patterns with multiple regions of local symmetry; and (3) the step-by-step construction sequence of each specific pattern must be individually memorized or kept in documentary form. From the historical perspective, there is scant evidence from surviving documents that the geometric artists of Muslim cultures used this methodology. By contrast, the polygonal technique is immanently suited to creating original designs, is the only methodology that allows for the creation of the most highly complex patterns found in this tradition, and its inherent flexibility allows the artist to create an unlimited number of designs without having to memorize construction sequences. What is more, there is significant evidence for its historical use. By contrast, the only known source of evidence for what I am herein referring to as point-joining is the anonymous Persian language treatise *On Similar and Complementary Interlocking Figures* in the Bibliothèque Nationale de France in Paris. The section of Chap. 2 that is concerned with point-joining addresses my speculations on the historical relevance of this document in considerable detail. This is an important treatise for many reasons, not the least of which is that it is the only known historical document that provides step-by-step written instructions for creating a number of Islamic geometric patterns. This feature has led some to conclude that the methodology demonstrated in this anonymous treatise is reflective of that used by Muslim geometric artists of the past. My hypotheses are somewhat less generous to the methodological significance of this document. The third methodological approach discussed in Chap. 2 makes use of geometric grids from which pattern lines are extracted. This methodology employs either the orthogonal or isometric grid, and many of the early patterns of low or moderate complexity can be constructed with this technique. It is worth noting that these same designs can often be alternatively created from either the polygonal technique or point-joining, and it is often impossible to know for certain which methodology the artists of a given example used. The use of the orthogonal grid will frequently produce patterns that require geometric adjustment to the proportions of the design. For example, when locating the points of an eight-pointed star upon the vertices of the orthogonal grid, the eight points will not be equal. In such incidences, it is necessary to engage in corrective measures to bring the design into compliance with the aesthetics of this tradition. In the hands of skilled practitioners, the orthogonal grid can be used to create geometric patterns of considerable sophistication. This variety of design and methodological approach has been thoroughly explored by Jean-Marc Castéra in his excellent book *Arabesque*,² and is therefore only touched upon in this work. Another methodological approach that is included in this section involves offsetting of the lines that make up a radii matrix so that two parallel lines are produced. These are then extended and trimmed with other offset and extended lines to create the finished pattern. I refer to this method as *extended parallel radii*. There are very few designs from the historical record that fall into this category, but their distinguishing aesthetic

² Castéra 1999.

qualities merit their inclusion in this work. The final methodology covered in this chapter is *compass-work*. Many of the earliest Islamic geometric patterns were created from a matrix of circles set upon a repetitive grid, and trimmed to create the final design. This technique produces designs with a distinctive character that often parallels the earlier Hellenistic geometric ornament from which it derived. Compass-work was soon surpassed by other more flexible design methodologies, but occasional examples are found throughout the historical record. This chapter on differentiation within this geometric idiom concludes with a description of the various conventions governing line treatment within this tradition.

Chapter 3 provides a thorough analysis of the methodological practices associated with the polygonal technique. The illustrations of historical examples that accompany this chapter do not attempt to reproduce the colors and secondary background motifs such as floral designs or calligraphic inserts. Rather, by showcasing just the geometric designs themselves these illustrations are intended to more effectively demonstrate the geometric quality of these patterns. The illustrations in Chapters 2 and 3 were produced by me using a combination of software programs, including AutoCAD®, Rhino3D®, and Adobe Illustrator®. The illustrations in Chapter 3 include multiple examples of underlying generative tessellations that are associated with the geometric designs themselves. In some cases, I have demonstrated how a single pattern can be produced from more than one underlying tessellation, and that these alternative tessellations frequently have a dual relationship. Here again, it is not always possible to know which underlying polygonal tessellation was used to create such examples. This chapter also examines various historical conventions for arbitrarily introducing design modifications that significantly alter the visual quality of the finished pattern. The subdivisions within this chapter follow an analytical approach rather than the chronological approach of Chap. 1. Within this chapter as a whole, and within each subdivision of this chapter, the cited examples move from more simple structures to the more complex; and as this is also a general trend within the historical development of this tradition, there is a degree of similitude between the sequential order of the examples from both these chapters. The opening of Chap. 3 is focused upon the five historical design systems. This is followed by the nonsystematic use of the polygonal technique. The penultimate section of this chapter is concerned with dual-level designs and the chapter concludes with the application of the polygonal technique to non-Euclidean surfaces such as domes, half domes, and spheres. I have provided each of these sections with ample illustrations to demonstrate the high degree of diversity, subtlety, and geometric sophistication that characterizes this tradition. I have occasionally included patterns of my own creation as a means of demonstrating the further potential of specific underlying polygonal tessellations, or specific methodological practices. In some cases, this opens new avenues for further design innovation, for example the creation of multilevel recursive designs with true quasicrystallinity. While this chapter is not intended as an instruction manual, it is nonetheless hoped that it will help provide a methodological understanding that can be applied by dedicated artists, designers, and architects who have an interest in augmenting their work with this exceptionally beautiful form of geometric art.

Chapter 4 has been contributed by Craig Kaplan of the Cheriton School of Computer Science at the University of Waterloo in Ontario. This chapter is concerned with the use of computer algorithms to generate Islamic geometric patterns. There is considerable interest in creating geometric designs in this fashion, and Craig Kaplan is the leading authority in this application of computer technology. The obvious advantage of using computer algorithms is the rapidity of results, and the concomitant ability to explore and compare many design options with great fluidity. The algorithmic procedure prescribed in this chapter employs the same variety of underlying polygonal tessellations as were used historically and is therefore a contemporary expression of an ancient methodological practice. What is more, as amply demonstrated, the synergistic dynamic between the inherent flexibility of the polygonal technique and the ability to explore new geometric territories through the power of the computer opens new vistas of creative innovation.

This book is the culmination of many years working with Islamic geometric patterns. As a child I was always attracted to geometric design and long before seeing my first Islamic geometric pattern in a book, I spent long hours drawing radial geometric patterns with stars as primary motifs. As a teenager I began to work seriously with geometric art. My father was a professor of organic chemistry, and happening upon one of his plastic templates used for drawing molecular diagrams essentially determined the trajectory of my life's work. This template had perforations for each of the polygons from the triangle to the dodecagon, and with this I was able to explore the tessellating properties of numerous polygons in diverse configurations. I soon discovered that I could place lines at strategic locations of these tessellations, such as the vertices and midpoints of the polygonal edges, and that discarding the initial tessellation would thereby create attractive geometric designs. In time, as a young teenager, I saw my first Islamic geometric patterns in a book on Islamic architecture and was amazed at the similarity, and in some cases exactitude, of my creations with the patterns of long past Muslim artists. Thus began my lifelong fascination with Islamic geometric design specifically, and Muslim cultures, art and history more generally. I've had the good fortune to live and travel widely amongst Muslim cultures and have developed great respect and appreciation for the people I have encountered along the way and have the privilege to call my friends. I received my master's degree in this field in 1983 from the Royal College of Art in London, after which I began my professional career as an ornamental design consultant specializing in architectural projects for Muslim clients. I have had the honor of working on many significant buildings, including the expansion of the Prophet's Mosque in Medina and the expansion of the Grand Mosque in Mecca. I also designed the ornament for the new minbar of the Kaaba in Mecca. For many years and on four continents, I have lectured and taught design seminars on the subject of Islamic geometric design. I have also contributed several publications in this field. However, I chose design consulting over academia as a career and have remained an unaffiliated scholar of this discipline. Throughout my career I have continued my research and exploration of Islamic geometric patterns, always striving to better understand the methodological working practices that sustained this tradition for such a long period, and to apply these techniques to an expanding repertoire of original designs. I have been particularly concerned with the gathering of evidence for the historical use of the polygonal technique. In 1981, while attending the Royal College of Art, I received a letter from my friend Carl Ernst, now the Kenan Distinguished Professor of Religious Studies at the University of North Carolina at Chapel Hill, recommending that I seek out the work of Ernest Hanbury Hankin. These publications were still relatively obscure at this time, and reading Hankin's work provided my first confirmation that the method of using underlying polygonal structures to extract geometric patterns was historical. Soon after this I had occasion to study an illuminated frontispiece from a fourteenth century Mamluk Quran at the British Library. The scribed lines of the underlying polygonal tessellation that produced the fivefold geometric pattern were faintly detectable beneath the painting when viewed from an oblique angle. By far the most significant source of confirmation was my good fortune in seeing and photographing the Topkapi scroll while it was on temporary display at the Topkapi Museum in 1986 during a business trip to Istanbul. Unfurled before me was a large catalogue of excellent geometric designs, many of which included their underlying generative tessellations. From the perspective of historical design methodology, the significance of this document cannot be overstated. During the years of ongoing research I also found multiple architectural sources of evidence, including a niche from the *iwān* of the Sultan al-Nasir Hasan funerary complex in Cairo (1356-63), several Mughal jali screens, a Seljuk fritware tile in the collection of the Los Angeles County Museum of Art, and a Karamanid walnut door in the collection of the Museum of Turkish and Islamic Art in Istanbul. For many years I kept my discoveries concerning the polygonal technique strictly confidential, but in the early 1990s I resolved to make my findings available to the public via lectures and design seminars. Eventually I turned my sights toward publication. The first draft of this book was completed and copyrighted in

2000. This manuscript was accepted for publication by Springer in 2007. The comments from one of Springer's anonymous reviewers were particularly persuasive and led to my completely rewriting the book into its current form over these past 10 years.

It is my pleasure to register my sincere appreciation of the many people and organizations that have been supportive of my research over the years. I will begin by thanking most sincerely Ann and George Hogle for paying my tuition fees to the Royal College of Art during my master's degree. Such artistic patronage and selfless generosity is rare, and I remain forever grateful. I thank the technical staff, lecturers, senior lecturers, and professors at the Royal College of Art. My work in the Department of Painting and Printmaking and the Department of Ceramic and Glass, and as a postgraduate Research Fellow prepared me for my career as a design consultant specializing in Islamic architectural ornament. I thank the organizers of the annual Bridges Conference who accepted my first paper on the subject of self-similarity within Islamic geometric art, and honored me as their plenary keynote speaker at their 2003 conference in Granada. In particular, I thank the late Professor Reza Sarhangi of the Department of Mathematics at Towson University in Maryland who was the heart and soul of the Bridges Organization, and remains an inspiration to everyone fortunate to have known him. He was a skilled designer of Islamic geometric patterns in his own right and was a supportive friend throughout the many years of knowing him. I extend my sincere thanks to my aforementioned friend Professor Carl Ernst for translating selections of relevant text from the *Fi tadakhul al-ashkal al-mutashabiha aw al-mutawafiq* (On Similar and Complementary Interlocking Figures), an anonymous Persian language treatise at the Bibliothèque Nationale de France. I am grateful to the Aga Khan Visual Library for providing me with access to their extensive collection of photographs of Islamic architecture—both before and after this was made available as an online resource. I am particularly grateful to their former senior administrator Jeffery Spurr for having been so helpful during my initial research while visiting their substantial photographic archive in Cambridge, Massachusetts; and more recently to Michael Toler, the Archnet Content Manager, for his valuable assistance in obtaining photographic permissions. I am profoundly grateful to Professor Jan Hogendijk of the Mathematics Department at the University of Utrecht. His recommendation to Springer of my initial manuscript led directly to the publication of this book, and his publications and specialized knowledge of the history of Islamic mathematics have been a very helpful resource during the preparation of this manuscript. I am equally grateful to Professor Gülru Necipoğlu, the Director of the Aga Khan Program of Islamic Architecture at Harvard. Her seminal book on the Topkapi scroll is the single most important work on the subject of Islamic geometric ornament and has been of paramount importance to my own research—as doubtless that of many others. Her interest in my methodological approach during our first meetings at Harvard in the late 1990s was more helpful to me than she probably realizes. I am particularly grateful for her critique of my interpretation of the methodological significance of the anonymous Persian language treatise *On Similar and Complementary Interlocking Figures*. I thank Hüseyin Sen for his continued interest and support of my work as a lecturer and teacher of this geometric discipline. His dedication to the history of science in the Islamic world is detailed and inspiring. My participation in the Islamic geometric design program that he helped organize at the Lorentz Center at the University of Leiden was an exceptional experience, and his more recent leadership in organizing the *International Workshop on Geometric Patterns in Islamic Art* in association with the Istanbul Design Center has been deeply rewarding. I also thank the staff and administrators of the Istanbul Design Center for their overwhelming hospitality and professionalism. I am very grateful to Carol Bier for her patience and helpful insight during our many conversations relating to the content of this book. I would like to express my thanks and utmost respect to Jean-Marc Castéra for his second-to-none dedication to this discipline. Although we have different methodological approaches, our differences only bring us closer—would that this were the way of the world. I also extend my appreciation to other specialists of Islamic geometric design who

have made valuable contribution to this field of study, including: Emil Makovicky, Anthony Lee, Peter Cromwell, Mirek Majewski, Rima Ajlouni, and Eric Broug. Their dedication is inspiring. I also give my special thanks to my close friends John Bussanich and Michael Baron for their ongoing interest and encouragement in the protracted progress of this book.

I would be remiss in failing to acknowledge my appreciation and gratitude to multiple authors of previous published works on the subject of Islamic geometric design. Of particular significance to my work in this field have been the publications of previously mentioned specialists, including Ernest Hanbury Hankin, Gülru Necipoğlu, Jean-Marc Castéra, Craig Kaplan, Anthony Lee, and Peter Cromwell. I highly recommend the work of each of these authors to those interested in expanding their understanding of this fascinating art form. I am also greatly indebted to Gerd Schneider for his exhaustive survey of Seljuk geometric patterns in Anatolia. I have relied heavily upon his catalogue of designs in my own formulations concerning the methodological analysis and historical development of the geometric ornament produced during the Seljuk Sultanate of Rum.

I would also like to acknowledge my students. Over the years I have had the privilege of instructing a number of very talented individuals, and the work of these students has frequently been inspiring and illuminating. I am always fascinated by the high level of idiosyncratic style that is possible within a discipline that can mistakenly be thought of as rigid and devoid of personal expression. In particular I want to extend my appreciation to Marc Palletier and Amina Buhler Allen. Their dedication to this discipline includes the education of young children in the use of polygonal systems to create Islamic geometric designs. Marc Palletier has become a highly skilled designer of Islamic geometric patterns who has contributed several significant innovations to the systematic use of the polygonal technique. I am immensely grateful to him for putting me in touch with Sir Roger Penrose.

I am very grateful to my editors at Springer. They have been a pleasure to work with and their patience has been greatly appreciated. I could not be in better hands. I am solely responsible for the content of Chaps. 1, 2, and 3. This work covers a tremendous amount of territory and despite my best efforts, there are bound to be some mistakes. I take full responsibility for any and all such flaws, hope that these are of an insignificant nature, and thank my readers for their indulgence. I also hope that I have succeeded in not coming across as a methodological absolutist in my advocacy of the polygonal technique. It is always important to keep in mind the flexible nature of this design tradition, and the fact that many of the historical examples from this tradition can be created from more than a single technique. Mindful of this, I apologize if I occasionally overemphasize my commitment to the primacy of the polygonal technique with statements such as “created with the *system of regular polygons*,” especially if this appears to suggest that no other design methodology may have alternatively been used. This is especially relevant in examining the less complex patterns that can often be created with diverse approaches. In recognition of the relevance of other design methodologies, and acknowledging the valuable contributions of specialists who advocate for these, I welcome alternative views and further contributions to this subject.

As stated, there is a significant amount of repetition within this manuscript, with historical examples of given designs provided multiple times. Within the opening section of this book, this repetition has resulted in large part due to the need for historical context in emphasizing the aesthetic continuity between Muslim cultures. Similarly, within the section devoted to design methodology, the specifically historical examples that are included are additionally identified with their historical locations. Again, this is for the purpose of identifying the cultural context of these many patterns: in some cases specific to a single Muslim culture, and in others, used ubiquitously throughout the Islamic world. I therefore thank the readers of this book for patiently accepting the degree of repetition as a necessary vehicle for providing historical context and continuity.

I want to thank the many photographers who have agreed to have their work included in this book. In particular I am grateful to Thalia Kennedy for her photographs from Afghanistan and Central Asia, to Jean-Marc Castéra for his photographs from Iran and for providing a photograph of himself drawing a design freehand, to Tom Goris for his photographs of the northeast dome chamber of the Friday mosque at Isfahan, to Bernard O’Kane for allowing me to use his photographs from Afghanistan and Central Asia, and to Daniel Waugh for providing photographs from Iran and China. I am especially grateful to David Wade for making his substantial archive of photographs available to the public via his website, *Pattern in Islamic Art*, and for allowing me to use so many of his excellent photographs within this book. I am also indebted to Marcus Baron for providing the excellent renderings for the seven spherical designs in Chapter 3. I extend my sincere thanks to Craig Kaplan for agreeing to provide the concluding chapter of this book concerning the use of computer algorithms to generate Islamic geometric patterns. In addition to his work as a computer scientist, he is a highly skilled designer and geometrician and has been a valued friend and associate for many years. I am very pleased to include his most worthy contribution to this publication.

I am immensely honored and very grateful to Sir Roger Penrose for agreeing to write the foreword to this book. Sir Roger is the distinguished Emeritus Rouse Ball Professor of Mathematics of the Mathematical Institute at the University of Oxford. His reputation as one of the world’s leading mathematical physicists and cosmological theorists precedes him, but some might be less aware of his pioneering work in geometry. In the early 1950s his forays into visual geometric illusions were an influence upon M. C. Escher. Of particular relevance among those interested in Islamic geometric design is Sir Roger’s discovery of Penrose tilings in 1974. These are comprised of two prototiles that have edge conditions that force aperiodicity—known appropriately as Penrose matching rules. Penrose tilings have fivefold symmetrical characteristics, and in addition to aperiodicity they will recursively inflate and deflate to produce infinitely scalable self-similar structures. Penrose tilings anticipated the discovery of fivefold quasicrystalline compounds in nature, and more recently, and to considerable fanfare, have been attributed to the structure of several examples of Persian geometric design. My own analysis of these cited Persian examples reveals that each is in fact governed by translation symmetry and therefore does not meet the aperiodic criteria of quasicrystallinity. Yet as a design professional, it could be regarded as quixotic to challenge the scientists who first promulgated this theory. It is therefore the greatest satisfaction to have the support of Sir Roger Penrose who is without question the foremost authority on this subject. His interest and support of my work and propositions pertaining to Islamic geometric design means more than I can adequately express.

I am also without words to properly articulate my heartfelt appreciation to my family who have patiently endured my 18 years of work on this book. I thank my parents and siblings for their longstanding interest, as well as my wife’s remarkable family for their sustained encouragement over the years. More than anyone else, I extend my love and appreciation to my ever patient and supportive wife, Shireen, without whom this book could not have been written. Likewise my heartfelt love and thanks to our daughter, Mehera, son-in-law, James, and to our beloved grandchildren for being constant sources of inspiration in every aspect of my life.

Finally, I thank my readers. I hope the historical, geometric, and methodological content of this work contributes to the greater understanding and appreciation of this remarkable and uniquely beautiful artistic tradition. For contemporary artists and designers of Islamic geometric patterns there is still a vast expanse of innovative potential waiting for exploration. This includes new and original systematic and nonsystematic patterns that build upon the repertoire and aesthetics of traditional work, designs with diminishing scale, parquet deformations as per the work of Craig Kaplan, multiple-level designs with self-similarity, aperiodic designs with true quasicrystallinity, and non-Euclidean designs with spherical, hyperbolic, and irregular

topographical geometry. This world needs more beauty, and I hope that this book will help to inform and inspire those with a sincere desire to embark upon such explorations. And in doing so, it is my further hope that this book may contribute to the rekindling of this remarkable artistic discipline so that it can become an evermore-active vehicle of contemporary artistic expression.

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of Construction

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