Viruses and Crystals: Science Meets Design

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Abstract

This paper presents a review of the development of X-ray crystallography – the science of determining the arrangement of atoms in solids – a discipline that encompasses physics, chemistry, biology, mineralogy and mathematics. The importance of the cross-fertilization of ideas between the arts and sciences is discussed and examples are provided.

Introduction

The presence of symmetry in nature has long fascinated both scientists and artists. For centuries geometry has been used as a tool across the disciplines by artists, engineers, biochemists, physicists and mathematicians, to understand, explain and order phenomena in the world around us. Biologist and philosopher Ernst Haeckel made detailed studies of microscopic life forms exhibiting unusual symmetric characteristics, illustrating over 4,000 species of radiolaria [1] (see Figure 1). In 1940, French structural innovator Robert le Ricolaris proposed a geodesic shell structure based on triangulated networks of radiolaria [2]. Buckminster Fuller's independent innovation of the geodesic dome, dating from 1948, also displays a similar structure to many radiolaria. Fuller's ideas on geodesic structures stimulated significant scientific developments, with the 1985 discovery of a super-stable all-carbon C60 molecule, appropriately named *Buckminsterfullerene*. Variants of this form, collectively known as *fullerenes*, have been the subject of intense research as they offer great potential as new materials in various branches of engineering. Fuller's ideas also had an impact in the field of virology when scientists again drew ideas from the structure of his geodesic domes in the quest to understand the structure of virion protein shells [3]. A model depicting the icosahedral structure of the adenovirus is shown in Figure 2; the similarities between its structure and the radiolaria depicted by Haeckel are clearly evident.

Science and the creative disciplines of art and design are usually considered as polar opposites, although both rely on a process of observation, experimentation and synthesis. An elegant example of the connections between science and the arts is demonstrated in the parallels between crystallographic theory and pattern design and analysis, both of which are underpinned by geometry. Crystals are made up from a regular arrangement of unit cells, of an identical shape and content, with each unit cell containing one or more molecules, packed together in a symmetrical way. In a similar manner, the possibilities for the design of two-dimensional patterns rely on the creation of one or more motifs, which are arranged in a symmetrical manner. The renowned work of Dutch graphic artist M.C. Escher was enhanced through his introduction to crystallography by his half brother B.G. Escher, who realised his '*regular divisions of the plane'*, applied a two-dimensional crystallography [4]. Escher owed much to the illustrative material of Pólya [5] and Haag [6] and in turn, Escher's divisions of the plane captured the imagination of scientists with his extensive investigations into the coloring of his motifs anticipating the work of crystallographers by 20 years.

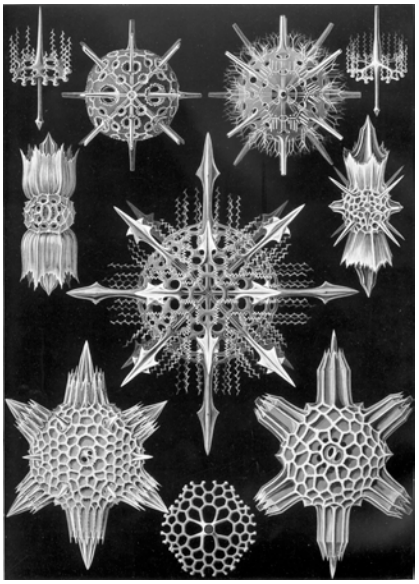

Figure 1 *Plate 41 from Haeckel's 'Kunstformen der Natur' (1904), depicting radiolarians classified as Acanthophracta*

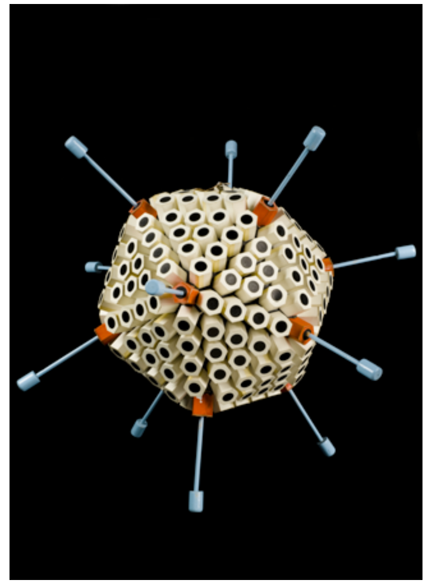

Figure 2 *Model of adenovirus, England, 1974-1976, Science Museum/SSPL*

This paper discusses the exchange of ideas between crystallography and design, reviewing how these disciplines inspired each other in the mid-twentieth century, culminating in the work of the Festival Pattern Group, which was exhibited as part of the 1951 Festival of Britain. In the same era, X-ray crystallography was applied to determine biomolecular structure, resulting in the emergence of the new field of molecular biology. The importance of geometry as a tool to understand and explain phenomena across the disciplines is highlighted as a significant connection between interrelated ideas developed in science, architecture and design.

Pattern in Crystal Structure

Until the twentieth century archeologists, anthropologists and design historians had restricted their study of pattern on decorated objects to broad ranging and subjective commentary, unaware of a uniform system of classification. The early-twentieth century saw the evolution of a new perspective in pattern analysis – the consideration of patterns by reference to their symmetry characteristics. Originating in the scientific investigation of crystals, this approach was pioneered by the Russian crystallographer Federov [7], who in the late-nineteenth century determined the 230 three-dimensional crystallographic groups before proving that plane patterns are constructed in accordance with the 17 plane crystallographic groups. However, it was not until the 1920s that interest in the enumeration of the plane crystallographic groups was aroused through the work of Pólya [5] and Haag [6]. These advances came about through the invention of the technique of X-ray diffraction in the analysis of crystallized structures.

The development of X-ray crystallography during the twentieth century allowed the study of matter at sub-atomic level and the depiction of the arrangement of atoms within a molecule. W.H. Bragg, and his son W.L. Bragg, who pioneered the use of X-ray diffraction techniques as a method for determining crystal structure, laid the foundations of this science in 1912. Developments in the application of X-ray diffraction continued and W.T. Astbury, who used X-ray crystallography to establish the relationships between the molecular structure, anatomical form and physical performance of textile fibers, made important contributions in the context of textiles. Today Astbury is widely credited with the definition of the field of molecular biology [8]. The textile physicist, H.J. Woods, working with Astbury in the 1930s, realised the potential benefit of this knowledge to textile designers, presenting a geometric framework for the design of textile patterns [9]. Conceptually several years ahead of theoretical crystallographic developments worldwide, Woods is recognised for laying the foundation of current thinking in the area of pattern geometry.

By the 1940s, X-ray crystallography had become one of the most significant branches of science of the time. Although much of the explanatory literature was not readily accessible to design practitioners, the application of crystallographic theory to pattern design was readily apparent to the scientific community. This shared geometric framework assisted in the visual explanation of this exciting new science. From the early days of X-ray diffraction, the Braggs frequently used examples of wallpaper designs to explain the principles of crystallography. Realizing the design potential offered by crystal structures, crystallographer Helen Megaw proposed that crystal structure diagrams and contour maps could be themselves used as motifs in the design of textiles. The idea was pioneered by Mark Hartland Thomas, chief industrial officer at the Council of Industrial Design, and the Festival Pattern Group was formed from a collective of leading manufacturers who were invited to produce furnishings and interior products decorated with crystal structure designs for the 1951 Festival of Britain, with Megaw as scientific consultant. Working as Assistant Director of Research at Cavendish Laboratory in Cambridge where W.L. Bragg was building a world-class team of crystallographic researchers, Megaw's influence saw that the design inspiration was supplied by many of the leading crystallographers of the day [10].

Figure 3 *Insulin 8.27 diagram by Dorothy Hodgkin, late 1930s, V&A Images/Victoria and Albert Museum*

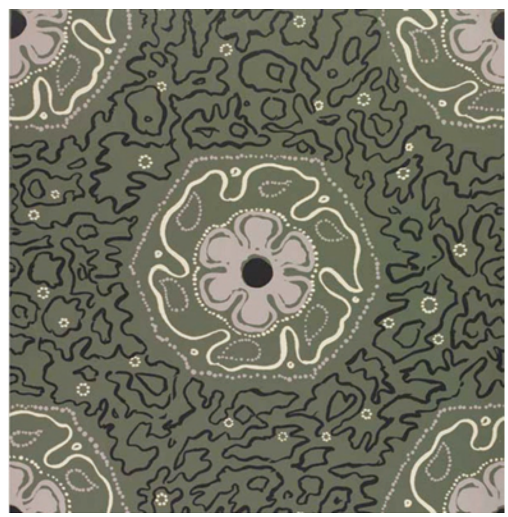

Figure 4 *Insulin 8.27 wallpaper, Festival Pattern Group, 1951, V&A Images/Victoria and Albert Museum*

The authenticity and accuracy of the scientific imagery and its interpretation was key to the work of the Festival Pattern Group as shown by Figures 3 and 4, which illustrate the contour map of insulin and its interpretation as a wallpaper design. Although, as Hartland Thomas pointed out, crystallography was not provide a convenient short cut to good design but acted as a catalyst for design inspiration [11]. While the pattern design had their origins in crystal structure diagrams, the scale, materials, production method and intended end use resulted in different aesthetic appeal for designs derived from the same scientific source. Despite the success of the Festival Pattern Group and the efforts of the Council of Industrial Design to stimulate a new design aesthetic, the influence of crystal patterns on the design industry was short-lived. See [10] and [11] for detailed discussion on the work of the Festival Pattern Group.

Crystallography, Tiling and Virus Structure

The use of X-ray crystallography as a method for determining the structure of biological molecules began in the 1920s. Complex crystal structures of proteins began to be solved by the late 1950s and at a similar time the field of structural biology began to emerge when Crick and Watson [12] published their theory on virus structure. Numerous crystal structures of proteins, nucleic acids and other biological molecules have since been determined and scientists can now study large macromolecular assemblies such as viruses.

A virus particle consists of two chemical components: a core composed of nucleic acid and a shell, known as a capsid, which is made from a network of individual proteins. Crick and Watson [12] reasoned that the protein shell was composed of identical subunits and, presuming specific bonding between subunits, they must be packed together in a symmetrically regular manner. Using this idea they predicted that spherical viruses might have tetrahedral, octahedral or icosahedral symmetry. The frequent occurrence of icosahedral symmetry was thought to be due to the principle of economy as the structure provides the most efficient packing of subunits. Pawley [13] suggested that the application of plane patterns onto polyhedra might be significant to the study of the structure of viruses, as folding plane lattice structures onto polyhedra can represent possible arrangements for subunits. This design project was independently undertaken [14] and returns to crystallographic ideas underpinning the creation of pattern designs and the geometric consideration of these in three dimensions. A design created whilst exploring the folding of plane patterns onto the icosahedron is shown in Figure 5.

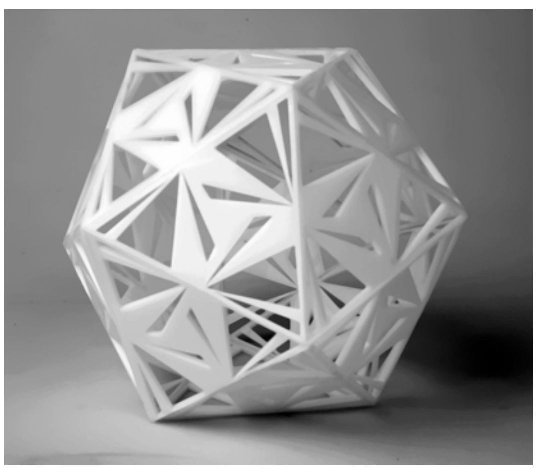

Figure 7 *Icosahedron #1, exploring the Crick-Watson theory, 2007.*

Findings by Franklin, Klug and Caspar suggested additional principles further to those associated with the Crick-Watson theory and drawing inspiration from architect R. Buckminster Fuller's geodesic domes and Kenneth Snelson's tensegrity structures, Caspar and Klug [15] enumerated all possible sub-triangulated icosahedral surface lattices in the development of their classic theory of virus structure. It was the publication of the first book on Fuller's work [16] that provided the virologists with the insight that stimulated the development of the Caspar-Klug theory of *quasi-equivalence*, a term conceived to describe the near-identical way in which large numbers of identical protein units form capsids by a self-assembly process, employing the concept of triangulation. Figure 6 provides an example of a model demonstrating the concept of quasi-equivalence and models illustrating the geometry of viruses are shown in Figure 7.

Figure 6 *Paper lattice model of quasi-equivalence in the structure of the capsid, Aaron Klug c.2000, MRC Laboratory of Molecular Biology*

Figure 7 *A selection of Aaron Klug's models in assorted materials to show the geometry of viruses, c.1960s, MRC Laboratory of Molecular Biology*

Conceptual developments have continued with the discovery of virus particles displaying skew triangular lattice structures, which were interpreted by Coxeter [17]. Twarock [18] proposed a generalized approach to the Caspar-Klug theory of quasi-equivalence based on tiling theory in order to account for the icosahedral capsids that had been observed experimentally but that are not covered by the Caspar-Klug model, a theory that was later extended to multi-level tilings. A series of pattern designs have been produced in response to the novel approach to the description of viral capsid assembly proposed by Twarock. Inspired by the biological imagery, in some cases reminiscent of Islamic patterns, and using concepts based on Penrose tilings the two types of face tiles shown in Figure 8a were produced. The faces of the rhombic triacontahedron in Figure 8b are tessellated with kites, darts and rhombs that are incorporated into the design of the tiles. The tiles were then manipulated to create the p6m repeating pattern design illustrated in Figure 8c, which is reminiscent of Islamic interlace patterns.

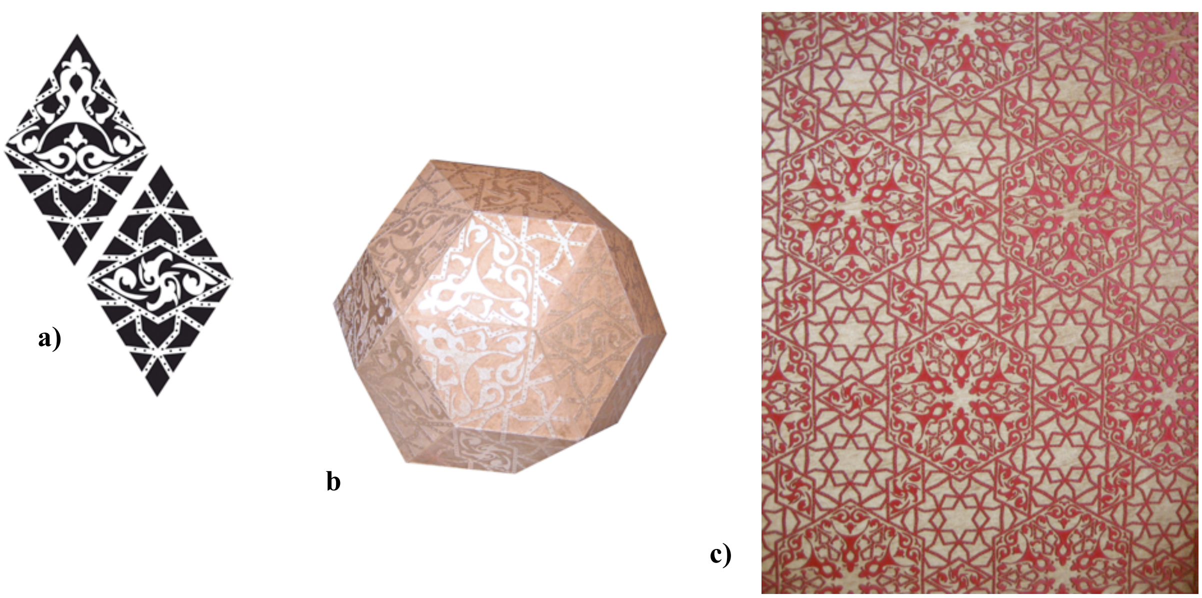

Figure 8 ***a)*** *Face tile designs for the rhombic triacontahedron* ***b)*** *"Reidun #1, painted and etched wood composite, 2010* ***c)*** *"Reidun #4, painted and etched wood composite, 2010*

Summary

The pioneering science discussed above was supported by visual scientific representations that are a rich source for artistic exploration. The use of geometric theories and models can lead to a better understanding of concepts in many areas of science and also lend themselves to more visual and creative interpretations, as demonstrated by Fuller's impact on scientific discovery. There is great value in the creative ideas that result from collaborative studies, which utilize knowledge of geometry as an elegant connection between the disciplines. Artists and scientists should be encouraged to make use of geometry as a means to explore problems together.

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