Mid-Century Molecular:
The Material Culture of X-ray Crystallographic Visualisation across Postwar British Science and Industrial Design

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Volume 1 of 2: Part One

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Copyright Statement

Abstract

This thesis investigates the use and significance of X-ray crystallographic visualisations of molecular structures in postwar British material culture across scientific practice and industrial design. It is based on research into artefacts from three areas: X-ray crystallographers' postwar practices of visualising molecular structures using models and diagrams; the Festival Pattern Group scheme for the 1951 Festival of Britain, in which crystallographic visualisations formed the aesthetic basis of patterns for domestic objects; and postwar furnishings with a 'ball-and-rod' form and construction reminiscent of those of molecular models.

A key component of the project is methodological. The research brings together subjects, themes and questions traditionally covered separately by two disciplines, the history of design and history of science. This focus necessitated developing an interdisciplinary set of methods, which results in the reassessment of disciplinary borders and productive cross-disciplinary methodological applications. This thesis also identifies new territory for shared methods: it employs network models to examine cross-disciplinary interaction between practitioners in crystallography and design, and a biographical approach to designed objects that over time became mediators of historical narratives about science. Artefact-based, archival and oral interviewing methods illuminate the production, use and circulation of the objects examined in this research.

This interdisciplinary approach underpins the generation of new historical narratives in this thesis. It revises existing histories of the cultural transmissions between X-ray crystallography and the production and reception of designed objects in postwar Britain. I argue that these transmissions were more complex than has been acknowledged by historians: they were contingent upon postwar scientific and design practices, material conditions in postwar Britain and the dynamics of historical memory, both scholarly and popular.

This thesis comprises four chapters. Chapter one explores X-ray crystallographers' visualisation practices, conceived here as a form of craft. Chapter two builds on this, demonstrating that the Festival Pattern Group witnesses the encounter between crystallographic practice, design practice and

aesthetic ideologies operating within social networks associated with postwar modernisms. Chapters three and four focus on ball-and-rod furnishings in postwar and present-day Britain, respectively. I contend that strong relationships between these designed objects and crystallographic visualisations, for example the appellation 'atomic design', have been largely realised through historical narratives active today in the consumption of 'retro' and 'mid-century modern' artefacts. The attention to contemporary historical narratives necessitates this dual historical focus: the research is rooted in the period from the end of the Second World War until the early 1960s, but extends to the history of now.

This thesis responds to the need for practical research on methods for studying cross-disciplinary interactions and their histories. It reveals the effects of submitting historical subjects that are situated on disciplinary boundaries to interdisciplinary interpretation. Old models, such as that of unidirectional 'influence', subside and the resulting picture is a refracted one: this study demonstrates that the material form and meaning of crystallographic visualisations, within scientific practice and across their use and echoes in designed objects, are multiple and contingent.

Contents

List of Illustrations

Introduction

Chapter One

6. X-ray diffraction photograph of a crystal of poliovirus by Aaron Klug and John Finch in 1959. The arrows marked on this photograph refer to so-called ‘spikes’ of high intensity registrations on the film. They relate to the scientists’ analysis of the symmetry of the virus structure. D.L.D. Caspar and A. Klug, ‘Physical Principles in the Construction of Regular Viruses’, *Symposia on Quantitative Biology: Basic Mechanisms in Animal Virus Biology*, *Volume 27* (Cold Spring Harbor, New York: 1962), 1-22 (p. 9).
7. Molecular model of penicillin by Dorothy Hodgkin (c.1945). © Science Museum / Science & Society Picture Library.
8. Diagram of a kaolinite (clay) mineral structure using circle-and-line notation showing locations of atoms at different elevations in the structure published British X-ray crystallographers George W. Brindley and Keith Robinson in 1946. G.W. Brindley and Keith Robinson, ‘The Structure of Kaolinite’, *Mineralogical Magazine*, 27 (1946), 242-253, p. 249.
9. William Wollaston’s model of close-packed hard spheres (early nineteenth century). © Science Museum / Science & Society Picture Library.
10. Geometrical diagrams of crystal structures in projection published by René Just Haüy in 1784. Plate 1 from René Just Haüy, *Essai d'une Théorie Sur la Structure des Crystaux* (Paris: Chez Gogué & Née de la Rochelle, 1784). Available at http://www.scs.illinois.edu/xray_exhibit /ImagePages/huayImage2.php. Accessed 24 November 2014.
11. Crystal structure diagram of the mineral perovskite in clinographic projection published by British X-ray crystallographer Helen Megaw in 1946. Helen Megaw, ‘G. Solids. Crystal Structure of Barium Titanium Oxide and Other Double Oxides of the Perovskite Type’, *Transactions of the Faraday Society*, 42 (1946), 224-231 (p. 224).
12. John Kendrew constructing a skeletal model of myoglobin, a protein found in some muscle tissue (dubbed the ‘forest of rods’) (c. 1960). MRC LMB Archive.
13. Space-filling model of ethanol made with components from the Courtauld Atomic Model Set produced by the London firm Griffin and George in the 1950s. © The Whipple Museum of the History of Science (Wh.5815). Available at http://www.hps.cam.ac.uk/whipple/explore/models/ modellingchemistry/. Accessed 23 September 2015.
14. Patterson map (reflecting data on potassium dihydrogen phosphate) published by Arthur Lindo Patterson in 1934. A. L. Patterson, ‘A Fourier Series Method for the Determination of the Components of Interatomic Distances in Crystals’, *Physical Review*, 46 (1934), 372–376 (p. 375).
15. Example of an electron density map relating to research on the structure of myoglobin by John Kendrew. G. Bodo, H.M. Dintzis, J.C. Kendrew and H.W Wyckoff, ‘The Crystal Structure of Myoglobin V. A Low-Resolution Three-Dimensional Fourier Synthesis of Sperm-Whale Myoglobin Crystals’, *Proceedings of the Royal Society of London A*, 253, p. 17.

16. Image of a poliovirus model published by Klug and the crystallographer John Finch in 1959. J.T. Finch and A. Klug, 'Structure of Poliomyelitis Virus', *Nature* (183) (20 June 1959), 1709-1714 (p. 1712).
17. Icosahedron. By Wikimedia Commons user 'DTR', Wikimedia Commons. Available at https://commons.wikimedia.org/wiki/File:Icosahedron.svg. Accessed August 2014.
18. A 1961 electron microscope image of a particle of the adenovirus. R.W. Horne and P. Wildy, 'The Architecture of Viruses', *Discovery*, October 1961, 425-431 (p. 425).
19. Segment of a 1959 *Observer* article on Klug's poliovirus research. Scientific Correspondent, 'New Light on How Polio Starts', *The Observer*, 21 June 1959.
20. Image of a Fuller geodesic dome as a figure in Caspar and Klug's 1962 paper. D.L.D. Caspar and A. Klug, 'Physical Principles in the Construction of Regular Viruses', *Symposia on Quantitative Biology: Basic Mechanisms in Animal Virus Biology* 27 (Cold Spring Harbor, New York: 1962), pp. 1-22 (p. 11).
21. Geodestix packaging c. 1959. Photographs by Emily Candela.
22. Demonstration of the flexibility of the plastic D-stix straw. Photograph by Emily Candela.
23. Figure from Caspar's 1980 paper showing Geodestix formations. D.L.D. Caspar, 'Movement and Self-Control in Protein Assemblies: Quasi-Equivalence Revisited', *Biophysical Journal*, 32 (1980), 103-138 (p. 111)
24. John Kendrew's Plasticine model of a molecule of the protein myoglobin made in 1957. MRC LMB Archive.
25. Electron density map associated with penicillin structure research by Dorothy Hodgkin, Barbara Low (Oxford), C.W. Bunn and A. Turner-Jones (I.C.I. Alkali Division, Northwich) (c. 1945). © Museum of History of Science, University of Oxford, 17631.
26. Single leaf of tracing paper '(b) (1)' showing hydroxides tilting diagram from Helen Megaw's laboratory notebooks (possibly c. 1935). Helen Megaw Papers, GCPP 5/3.
27. Superimposed diagrams on tracing paper '(b) (1)' and '(b) (2)' showing hydroxides tilting diagram from Helen Megaw's laboratory notebooks (possibly c. 1935). Helen Megaw Papers, GCPP 5/3.
28. Steel balls covered in paint from Bernal's packing experiment. J.D. Bernal and S.V. King, 'Experimental Studies of a Simple Liquid Model', in *Physics of Simple Liquids*, ed. by H.N.V. Temperly, J.S. Rowlinson, G.S. Rushbrooke (New York: John Wiley and Sons, 1968), pp. 233-252 (p. 238).
29. Bernal building a model of a liquid structure in his office in an undated photograph from collection of his colleague John Finney (probably c. 1959). John Finney, 'Bernal and the Structure of Water', *Journal of Physics*, 57 (2007), 40–52 (p. 41).

30. Aaron Klug's virus/geometric models exploring possible virus structure. MRC LMB Archive.

Chapter Two

1. Interior of the Regatta Restaurant. Mark Hartland Thomas, *The Souvenir Book of Crystal Designs* (London: CoID, 1951), p. 16.
2. Lace collar based on the crystal structure of the mineral hydrargillite for Regatta Restaurant waitresses designed by H. Webster for A.C. Gill. Science Museum, 1976-644/21.
3. Seats in the Exhibition of Science's cinema upholstered with fabric by ICI produced for the FPG. Hartland Thomas, *The Souvenir Book*, p. 15.
4. Front cover of *The Souvenir Book*. Hartland Thomas, *The Souvenir Book*.
5. Dyeline of a diagram of the mineral cristobalite submitted by Megaw to the FPG (detail). Helen Megaw Papers, AAD 1977/3/536.
6. Print of an electron density map diagram of the mineral afwillite submitted to the FPG by Megaw. Helen Megaw Papers, AAD 1977/3/576.
7. Dyeline of a Patterson projection diagram of insulin submitted by Megaw to the FPG. Helen Megaw Papers, AAD 1977/3/523.
8. Nylon diagram published by C.W. Bunn in 1947. C.W. Bunn and E.V. Garner, 'The Crystal Structure of Two Polymides ('Nylons')', *Proceedings of the Royal Society, Series A*, 189 (1016) (27 March 1947), 39-68 (p. 51).
9. Beryl diagram by Megaw for the FPG. Helen Megaw Papers, AAD 1977/3/518.
10. A diagram of nylon submitted by Megaw to the FPG. Helen Megaw Papers, AAD 1977/3/530.
11. A dyeline of a diagram of afwillite that Megaw submitted to the FPG. Helen Megaw Papers, AAD 1977/3/515.
12. Diagram of beryl structure published in Bragg's *Atomic Structure of Minerals*. W.L. Bragg, *Atomic Structure of Minerals* (Ithaca: Cornell University Press, 1937), p. 182.
13. Photographic print of tiled haemoglobin diagram (detail). Helen Megaw Papers, AAD 1977/3/517.
14. Perovskite structure drawn in projection, published by Megaw in 1946. Helen Megaw, 'G. Solids. Crystal Structure of Barium Titanium Oxide and Other Double Oxides of the Perovskite Type', *Transactions of the Faraday Society*, 42 (1946), 224-231 (p. 224).
15. Dyeline of a perovskite diagram prepared by Megaw for the FPG. Helen Megaw Papers, AAD 1977/3/569.
16. A Patterson diagram of the mineral afwillite published by Megaw in 1952. Helen Megaw, 'The Structure of Afwillite, $Ca_3(SiO_3OH)_2.2H_2O$', *Acta Crystallographica*, 5 (1952), 477-491 (p. 479).

17. Dyeline of tiled insulin diagram submitted by Megaw to the FPG. Helen Megaw Papers, AAD 1977/3/521.
18. Apophyllite diagram published by W. H. Taylor to which Megaw referred. W. H. Taylor and St. Naray-Szabo, 'The Structure of Apophyllite', *Zeitschrift Für Kristallographie - Crystalline Materials*, 77 (1931), 146–158 (p. 155).
19. Diagram of apophyllite published by Bragg to which Megaw referred. Bragg, *Atomic Structure of Minerals*, p. 227.
20. Working diagram of apophyllite structure by Megaw. Helen Megaw Papers, AAD 1977/3/475.
21. Copy of Megaw's apophyllite diagram submitted to the FPG. Hartland Thomas, *The Souvenir Book*, p. 10.
22. Megaw's working drawing, the basis for a dyeline of apophyllite structure submitted to the FPG. Helen Megaw Papers, AAD 1977/3/478.
23. Image of Warerite plastic sheet pattern designed by Martin O. Rowlands for the FPG. Hartland Thomas, *The Souvenir Book*, p. 11.
24. Megaw's working drawing (for her FPG diagrams) of an apophyllite structure. Helen Megaw Papers, AAD 1977/3/476a.
25. Working diagram of afwillite by Megaw marked 'Diagram 1'. Helen Megaw Papers, AAD 1977/3/512.
26. Working diagram of afwillite by Megaw marked 'Diagram 2'. Helen Megaw Papers, AAD 1977/3/513.
27. Working diagram of afwillite by Megaw, which is a tracing of Diagrams 1 and 2 (above) superimposed. Helen Megaw Papers, AAD 1977/3/514.
28. Figure included in Redgrave's *A Manual of Design*. Richard Redgrave, *A Manual of Design* (London: Chapman and Hall, 1876), p. 140.
29. Images based on mosaics from the Alhambra pictured in Jones' *The Grammar of Ornament*. Owen Jones, *The Grammar of Ornament* (London: Dorling Kindersley, 2001 [1856]), p. 221.
30. Pattern by Christopher Dresser showing the abstraction of botanical forms into repeated geometrical motifs that was typical of the South Kensington style. Christopher Dresser, *Studies in Design* (London: Studio Editions, 1988 [1876]), plate 23.
31. Example ornamental composition from an instructional drawing book by Walter Smith (c.1860s/1870s). Walter Smith, *Examples for First Practice in Freehand Outline Drawing: For the Use of Schools, and Adapted for Self-instruction* (Leeds: J. W. Bean, undated [c.1860s/1870s]), plate 44.
32. Carpet design representing a naturalistic style (the plants maintain an illusion of depth) by E.T. Parris for Turberville Smith & Co., shown at the 1851 Great Exhibition. Stuart Durant, *Victorian Ornamental Design* (London: Academy Editions 1972), p. 56
33. Megaw's working drawing of a lithium chlorate trihydrate diagram for the FPG. Helen Megaw Papers, AAD 1977/3/565.

34. Helen Megaw's 1921 examination book for 'Drawing (Design)'. Helen Megaw Papers, GCPP 2/2.
35. Detail from Helen Megaw's 1921 examination book for 'Drawing (Design)'. Helen Megaw Papers, GCPP 2/2.
36. Draft sketch by Megaw for her 1921 examination in 'Drawing (Design)'. Helen Megaw Papers, GCPP 2/2.
37. Hartland Thomas' 'House at Sneyd Park, Bristol'. F.R.S. Yorke, 'The Modern English House', *Architectural Review*, December 1936, 237-314 (p. 269).
38. Artist John Ernest with Polystyrene poliovirus model constructed based on Klug and Franklin's research in 1958 at Birkbeck College. MRC LMB Archive.
39. Artist John Ernest building Polystyrene tobacco mosaic virus (TMV) model based on Klug and Franklin's research in 1958 at Birkbeck College. MRC LMB Archive.
40. Diffraction photographs of diamond crystal by Kathleen Lonsdale, reproduced in Biederman's *Art As the Evolution of Visual Knowledge*. Charles Biederman, *Art As the Evolution of Visual Knowledge* (Red Wing, Minnesota: Charles Biederman, 1948), p. 572.
41. 'Construction in Brass' (1927) by constructivist artist Antoine Pevsner (brother of Naum Gabo), featured in Bierderman's *Art As the Evolution of Visual Knowledge* on the page facing Lonsdale's diffraction photographs in the figure above. Biederman, *Art As the Evolution of Visual Knowledge*, p. 573.

Part Two Introduction

1. 'Ball Clock' designed by Irving Harper for George Nelson Associates c.1948. Collection of the Brooklyn Museum. Available at: http://www.brooklynmuseum.org/opencollection/objects/2580/Ball_Wall_Clock/set/exhibition-1202#. Accessed 8 September 2014.
2. Ray and Charles Eames's 1953 'Hang-it-all' manufactured by Tigrett Enterprises. Collection of the Brooklyn Museum. Available at: http://www.brooklynmuseum.org/opencollection/objects/2605/Hang-It-All_Coat_Rack/set/exhibition-1202. Accessed 8 September 2014.
3. 'Anonymous' plastic ball-footed bin, wall-mountable coat hooks and umbrella stand pictured in a 2013 collectors' guide. Kate Beavis, *Style Your Modern Vintage Home: A Guide to Buying, Restoring and Styling from the 1920s to 1990s* (Devon: David & Charles, 2013), p. 71.
4. Ball-and-rod wall-mountable coat hooks pictured in a 1997 collectors' guide. Madeleine Marsh, *Collecting the 1950s* (London: Miller's, 1997), p. 78.

Chapter Three

1. Photograph of B12 model featured in an exhibition guide to the British displays from Brussels shown at the 1959 'Daily Mail Ideal Home'

exhibition. *The British Pavilion from Brussels Exhibited at the Daily Mail Ideal Home Exhibition, Olympia, London 1959* (London: Daily Mail Ideal Home Exhibition, 1959), p. 19.

2. Photographs of virus models shown at Brussels pictured in *The New Scientist* (1958). Lawrence Bragg, ‘An International Survey of Recent Scientific Research’, *The New Scientist*, 27 March 1958, 15-17 (p. 17).
3. Photograph of TMV model featured in the *Sunday Times* (1959). M.F. Perutz, ‘Living Molecules’, *Sunday Times*, June 14, 1959.
4. Photograph of standard lamp produced by Dernier & Hamlyn Ltd at the 1946 ‘Britain Can Make It’ exhibition. Design Council Slide Collection. Available at http://www.vads.ac.uk/x-large.php?uid=58510&sos=4. Accessed 26 May 2014.
5. Troughton & Young table lamp designed by A.B. Read pictured in *House and Garden*, May 1951, p. 25.
6. Photograph of ball-footed desk lamp produced by Merchant Adventurers Ltd and designed by Roger and Robert Nicholson at ‘Exhibition of European Light Fittings’, Glasgow, Scotland, 1950. DCA L1G3.
7. Photograph of ball-footed desk lamp with ball counterweight produced by Merchant Adventurers Ltd, published by *The Studio*. *Decorative Art: The Studio Year Book, 1951-2* (London: Studio Publications, 1951), p. 69.
8. Festival of Britain Homes and Gardens Pavilion ‘Music Lover’s Room’ designed by Robin Day, featuring Troughton & Young table lamp. Design Council Slide Collection. Available at: http://www.vads.ac.uk/large.php?uid=60339&sos=4. Accessed 28 August 2015.
9. Antelope seating at a Festival site in Northern Ireland (1951). Gordon Russell, ‘Northern Ireland’s Festival Exhibition: Ulster Farm and Factory’, *Design*, August 1951, 17-19 (p. 17).
10. Page from Gordon Russell and Alan Jarvis’s 1953 *How To Furnish Your Home* featuring the Antelope chair. Gordon Russell and Alan Jarvis, *How To Furnish Your Home* (London: Newman Neame, 1953), p. 10.
11. ‘Ultralux’ lighting in 1935 Troughton & Young ‘Ultralux’ catalogue. V&A National Art Library Trade Catalogues Collection.
12. Ceiling light designed by Hin Bredendieck at the Bauhaus. Christopher Wilk, ed., *Modernism: Designing a New World, 1914-1939* (London: V&A, 2008), p. 211.
13. Troughton & Young ceiling light (1935). 1935 Troughton & Young catalogue. Sidney William Hamlyn Papers, AAD 1996/10/89.
14. Dernier & Hamlyn ‘Neolux’ lighting (c. 1936).Dernier & Hamlyn catalogue, c. 1936. Dernier & Hamlyn Papers, AAD 1996/10/65.
15. Falk Stadelmann and Co light with chromium plated brass rod stem. *Decorative Art: The Studio Year Book, 1955-6* (London: Studio Books, 1955), p. 130.
16. A.B. Read’s 1948 ‘Versalite’, with aluminium shades, brass sphere and chromium-plated steel rod. Manufactured by Troughton & Young. V&A, M.213-2011.

17. Advertisement for ‘atomic’ draught-sealing strips (1950). *Daily Mail Ideal Home Exhibition Official Catalogue & Guide* (London: Daily Mail Ideal Home Exhibition, 1950), p. 114.
18. My grandmother-in-law’s barely visible ball-and-rod magazine rack, with even less visible ball feet when in use. Photograph by Emily Candela.
19. Hiscock’s ball-and-rod lamp featured in *Architectural Design* (1953). Margot Moffett, ‘Interior Design’, *Architectural Design*, March 1953, p. 84.
20. Advertisement for Hiscock, Appleby & Co plant stand. *House and Garden*, October 1953, p. 82.
21. 1953 Hiscock advertisement. *House and Garden*, December 1953, p. 74.
22. Wireworms ball-footed lamp featured in ‘Christmas Extra’, *Woman*, November 1953, p. 23.
23. Heal’s catalogue featuring ball-and-rod furnishings. Heal & Son Ltd, ‘Present for Particular People’, 1953. V&A National Art Library Trade Catalogues Collection.
24. Heal’s catalogue featuring ball-and-rod furnishings. Heal & Son Ltd, ‘Present for Particular People’, 1955. V&A National Art Library Trade Catalogues Collection.
25. John Lewis ‘Shopping News’, 1953. John Lewis Archive 772/RX.
26. Photograph of display interior at 1954 ‘Daily Mail Ideal Home’ exhibition showing a ball-footed wireframe book stand on the mantle. Daily Mail Ideal Home Exhibition Archive, AAD 1990/9/66.
27. Wireworms stand at the 1954 *Daily Mail* Ideal Home Exhibition. Daily Mail Ideal Home Exhibition Archive, AAD 1990/9/66.
28. Page section from Jeanne Heal’s 1956 *Planning an Ideal Home*. Jeanne Heal, *Planning an Ideal Home* (London: Daily Mail Ideal Home Series, Associated Newspapers Ltd, 1956), p. 94.
29. Advertisement for ‘Do It Yourself’ magazine rack. *Do-It-Yourself*, February 1958, p. 180.
30. A 1958 Woolworths Annual Report picturing a ball-footed magazine rack with small shelf in the upper left alongside a lamp and vase. ‘Woolworth in the home’, *Woolworths Annual Report*, 1958. Collection of Paul Seaton.
31. 1964 image of a Woolworths display. Collection of Paul Seaton.
32. Advertisement for a ‘contemporary style’ ball-and-rod lamp by the Peerage brassware firm. *Ideal Home*, March 1957, p. 23.
33. Colplas Ltd advertisement for plastic ball-feet. *Ironmongers’ Standard Catalogue & Price List 1960-1961* (London: Whitefriars, 1960), p. 47.
34. Stewart Plastics Ltd advertisement for ball-footed coal bucket. *Good Housekeeping*, December 1960, p. 114.
35. Stewart Plastics fruit bowl featured in the trade journal *British Plastics*. Catherine Craig, ‘What’s in Store: Plastics Products for the Kitchen’, *British Plastics*, March 1958, p. 91.

36. Ball-and-rod umbrella stand pictured in ‘FOB+10’, *Design*, May 1961, 40-51 (p. 44).
37. Full-page photograph of a golf ball accompanying the article ‘FOB+10’, p. 38.

Chapter Four

1. Screenshot from first page of results of a search using the keyword ‘atomic’ on www.ebay.co.uk. Accessed 23 January 2014.
2. Screenshot of listing for ‘Vintage Retro Magazine Rack, Atomic Feet, Original Condition’ on ebay.co.uk. Encountered through a search using the keyword ‘atomic’ on www.ebay.co.uk. Accessed 22 January 2014.
3. Cover of a 2014 issue of *Vintage Explorer* magazine announcing an article inside on ‘Atomic homeware’, represented by an image of Nelson’s ball clock. *Vintage Explorer*, February/March 2014.
4. Screenshot of listing ‘Vintage 1950S/1960S Atomic Sputnik Wall Mounted Coat Hooks’. Encountered through a search using the keyword ‘atomic’ on www.ebay.co.uk. Accessed 22 January 2014.
5. Screenshot of part of a results list from an ebay.co.uk search using keyword ‘atomic’. www.ebay.co.uk. Accessed 22 January 2014.
6. Screenshot of eBay listing for a wall-mountable coat rack. www.ebay.co.uk. Accessed 7 October 2013.
7. Magazine rack in Christine’s home. Photograph by Christine.
8. Ms Pink’s ball-and-rod magazine rack (she had moved it onto the table from its prominent place by the fireplace for the photograph). Photograph by Ms Pink.
9. Screenshot of a page on the website Pinterest showing results of a search for users’ posts based on keywords ‘Festival Pattern Group’. www.pinterest.com. Accessed 17 September 2015.
10. Publicity image accompanying Channel 4’s description of the programme *The House the 50s Built* featuring presenter Brendan Walker in front of Warner’s FPG wallpaper pattern based on the structure of nylon. Available at: http://www.channel4.com/programmes/the-house-the-50s-built/episode-guide/series-1/episode-1. Accessed 17 September 2015.
11. The cover of the 1951 *Souvenir Book of Crystal Designs* published for the Festival display of the FPG prototypes (left) and cover of de Chadarevian, *Designs for Life* (right). Soraya de Chadarevian, *Designs For Life: Molecular Biology after World War II* (Cambridge: Cambridge University Press, 2002); Mark Hartland Thomas, *The Souvenir Book of Crystal Designs* (London: CoID, 1951).

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Author's Declaration

During the period of registered study in which this thesis was prepared the author has not been registered for any other academic award or qualification. The material included in this thesis has not been submitted wholly or in part for any academic award or qualification other than that for which it is now submitted.

Emily Candela
October 2015

Abbreviations

AAD	Archive of Art & Design (Victoria & Albert Museum)
BBC	British Broadcasting Corporation
BBC WAC	BBC Written Archives Centre
BoT	Board of Trade
CoID	Council of Industrial Design
DCA	Design Council Archive
DRU	Design Research Unit
FPG	Festival Pattern Group
GCPP	Girton College Personal Papers of Helen Megaw
ICA	Institute of Contemporary Arts
IG	Independent Group
LMB	Laboratory of Molecular Biology
MRC	Medical Research Council
SIA	Society of Industrial Artists
TMV	Tobacco Mosaic Virus
V&A	Victoria & Albert Museum

Introduction

In November 1959, the science writer Gerald Leach visited the Crystallography Department at Birkbeck College in London, seeking material for the BBC science television series *Eye on Research* for which he was a co-producer. What caught his eye during his visit were several models constructed from seemingly unconventional components. 'Excellent ping-pong ball models', Leach reported back to his colleagues, referring to his encounter with the virus models belonging to Aaron Klug, one of the department's scientists (Figure 1)[1]. At the time Klug was using X-ray crystallography to study the structure of the poliovirus, and models built out of ping-pong balls helped to visualise the subject of his research in three dimensions.

In highlighting these models, Leach had alighted on an important feature of postwar X-ray crystallography research: its visual and material nature. Scientists in this field used diagrams and three-dimensional models – drawn on Perspex or tracing paper, constructed out of ping-pong balls, Plasticine, balls-and-spokes or myriad other components and materials – to study and communicate about the atomic and molecular structures of matter, both organic and inorganic, at scales that were often otherwise invisible.

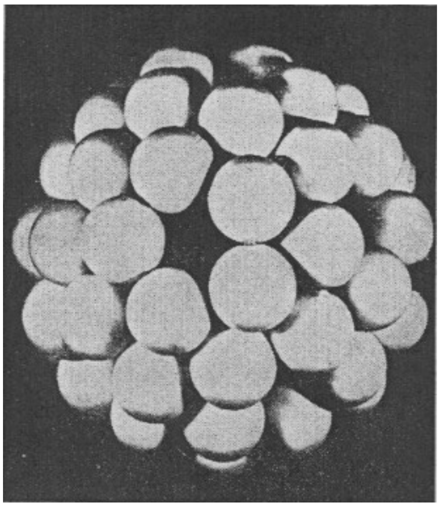

Figure 1 Ping-pong ball model of poliovirus associated with Aaron Klug's research (c. 1959).

[1] Note from Gerald Leach to Philip Daly and Aubrey Singer, 2 November 1959. BBC WAC, T14/1503/2.

That same year, the Cambridge X-ray crystallographer Helen Megaw was experimenting with different ways to draw a diagram of the structure of a feldspar mineral (Figure 2). Her sketches were not destined for a laboratory notebook or scientific publication. Instead, they were working drawings of a design for the cover of a booklet for an upcoming conference, the 1960 Congress of the International Union of Crystallography (Figure 3). As such, the purpose of these diagrams was largely aesthetic.

Megaw was, at this time, perhaps the crystallographer most likely to execute such a task. It reprised, in a small way, her work a few years earlier as scientific adviser to the Festival Pattern Group (FPG). The FPG was a collaboration bringing together manufacturers from several industries to produce household products bearing surface patterns based on X-ray crystallographers' diagrams, most of which were selected and drawn by Megaw. The project, which had been organised for the 1951 national exhibition the Festival of Britain, was short-lived; most of the group's prototypes were never commercially produced, much to Megaw's disappointment.

But she was able to revive the project, if only as a distant echo if its original form, a decade later for the 1960 Congress. Megaw asked Vanners & Fennel, an FPG textile manufacturer, to produce a run of one of their FPG ties (Figure 4). These had been popular with X-ray crystallographers in the aftermath of the Festival (back in 1951 Megaw wrote to the company, 'I am already getting inquiries from all my colleagues who want to know where their pet structure is obtainable'[2]). During the 1960 conference, attendees were directed to Shepherd's, a local Cambridge tailor, where they could find ties emblazoned with a pattern based on the atomic structure of clay.

[2] Helen Megaw to Bernard Rowland of Vanners & Fennell, 29 April 1951. AAD 1977/3/182.

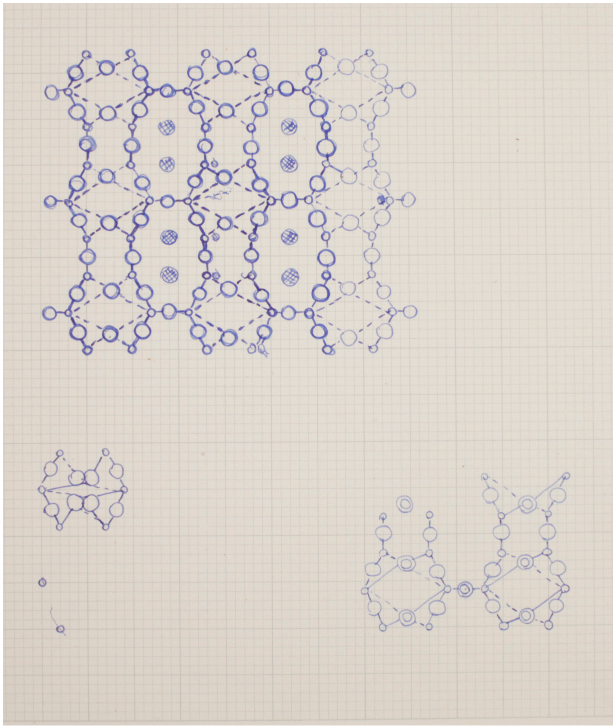

Figure 2 Working drawings by Megaw for the 1960 Congress booklet.

Figure 3 Final version of booklet cover designed by Megaw and produced by Heffer's, a Cambridge stationer (1960).

Figure 4 Ties produced by Vanners & Fennell for the FPG, pictured in 1951. The pattern of the tie on the left is based on a crystallographic diagram of the structure of china clay.

The year before we find Megaw sketching diagrams for the conference programme, a new Woolworths shop opened in Halesowen, in the West Midlands. A photograph taken on its opening day in September 1958 shows its shelves stocked with two items that are, for historians and 'retro' enthusiasts today, postwar archetypes: wall-mountable coat pegs made of metal rod with spherical finials are pictured in the foreground, and a stack of wire-frame magazine racks, arranged one inside the other, is just visible in one corner of the photograph, the ball-feet of some upturned racks sticking straight up (Figures 5 and 6).

Figure 5 Photograph from the opening day of a Woolworths store in Halesowen on 26 September 1958. Stacks of ball-footed magazine racks are just visible in the lower left corner of the photograph (some are stacked upside down inside of others).

Figure 6 Photograph of a postwar magazine rack of the same or similar model to those pictured in the above photograph of a 1958 Woolworths display.

In the late 1950s and early 1960s, Woolworths was a major retailer of household furnishings that are, like the magazine racks and coat hooks in the photograph, distinguished by a 'ball-and-rod' form and construction. Furnishings displaying this ball-and-rod motif became symbolic of the 'Festival' or 'contemporary' style promoted by the postwar government-sponsored Council of Industrial Design, due in part to the Festival debut of designer Ernest Race's ball-and-rod Antelope chair (Figure 7). In historiography on the subject, these furnishings are emblematic not only of the period's design for the home, but also its scientific discoveries. Historians identify the ball-and-rod forms of these objects with the ball-and-spoke molecular models produced contemporaneously in service of X-ray crystallography research. And within the market for 'mid-century modern' and 1950s 'retro' furniture today, these objects are identified by the appellation 'atomic'.

Figure 7 Antelope chair designed by Ernest Race.

The three types of artefacts introduced above - X-ray crystallographers' *visualisations* (meaning their models and diagrams), the objects that emerged from the FPG, and ball-and-rod furnishings - were produced in the same period and national context. They also share formal qualities, but they emanated from different fields and cultures of practice. In fact the examples above suggest widely disparate contexts. This raises questions. The most immediate one is quite simple: what kind of exchange between science and design fields in postwar Britain, if any, do these artefacts indicate?

Exploring this question brings us into encounter with larger more complex ones: What ideas, practices and material conditions shaped the production, use and circulation of these objects? What did the material and visual forms associated with crystallography mean to actors in different cultural spheres? Did scientific knowledge circulate in postwar British culture through these designed objects? And how did channels of communication, mediators or practices operating in both fields affect cross-field exchange? For instance, what aesthetic ideologies animating postwar British industrial design communities made it acceptable – or not - for a *designed* object intended for the homes of British consumers to reference a *scientific* object? If these artefacts did *not* emanate from such exchange, what does it mean for the way we write and remember the postwar histories of British design and science that these objects find themselves joined together today in historical narratives? And are the Festival of Britain and Council of Industrial Design (CoID) contexts, the focus of historiography on the designed objects introduced here, the right or only places to look for this history?

These concerns frame this project's investigation of the use and significance of X-ray crystallographic visualisations in postwar British material culture across scientific practice and industrial design. It proceeds through studies of the three kinds of objects described above: X-ray crystallographers' visualisations, artefacts associated with the FPG, and postwar ball-and-rod furnishings, which I examine both in terms of their postwar context and their consumption and reception today.

As the opening vignettes above insinuate, the set of cases that this thesis explores is quite disparate. It will take us from the crystallographer's laboratory to postwar British design promotion, to the production and consumption of modernist furniture in the period, and finally to the popular memory of science in twenty-first-century 'retro' culture. Although one might expect from the interdisciplinary subject area of this thesis that each episode will represent a neat intersection of 'science and design', or form part of a straightforward teleology, this is not the case. This fact reflects both the subject matter itself and my approach to it, which avoids clamouring after clear connections or encounters between crystallography and industrial design. An approach any less attentive to the slipperiness of the objects studied here would generate a limited picture of the use, forms and significance of X-ray crystallographic visualisation in postwar British science and design. As I will argue, disjuncture, ambiguity and retrospectively generated historiographical assumptions constitute just as much a part of this history of cross-field exchange as do discrete points of intersection. Acknowledging and understanding such facets of cross-field relationships are preconditions to producing nuanced, rich scholarship on their histories.

At this point it is necessary to briefly introduce what X-ray crystallography is: X-ray crystallography, which was developed in the early 1910s, involves the study of crystal structures. A crystal is made up of a regular arrangement of atoms that repeats in three dimensions. Postwar X-ray crystallography research included studies of both naturally occurring crystalline materials and laboratory grown crystals (of organic materials). X-ray crystallography's subject matter ranged from minerals to synthetic polymers to large complex molecules known as macromolecules, which include viruses and proteins.

On one hand, X-ray crystallography in the postwar period denotes a set of specific techniques centred on methods of directing X-rays through crystals to generate data about the structure of matter. On the other, it had the character of a scientific field, involving shared cultures of practice and common interests among its practitioners. It was therefore more than simply a set of specific techniques. Indeed by the postwar period, distinct centres of X-ray crystallography research had solidified in Britain (outlined in chapter one); a professional organisation of crystallographers, the International Union of

Crystallography, was established in 1948; and although X-ray crystallographers hailed from diverse scientific backgrounds, they were bound by a shared interest in the structure of matter.

My investigation of the three kinds of artefacts enumerated above forms a dramatic reassessment of existing historical narratives about exchange, communication and associations between X-ray crystallography and design in postwar Britain. Throughout I show X-ray crystallographic visualisation to be a less stable thing than has been assumed by much historiography. It is mutable and multiple in material form, use and meaning; its manifestations are contingent upon postwar scientific and design practices, aesthetic frameworks, material conditions and the dynamics of historical memory, both scholarly and popular. Associations between postwar crystallography and industrial design are in some ways only fully realised now. They surface in the historical memory operating in cultures of 'retro' (the consumption of period designed objects is central to such 'culture[s] of revival'[3]), and in published histories on the topic. Historiographical questions therefore arise throughout this investigation. These questions concern how the history of cross-disciplinary interactions in the past has been and can be written. This necessitated the dual historical focus of this research, which includes both the postwar past and the present.

This thesis opens up a new area of interdisciplinary research. As I explain below, the kind of historical investigation of the material culture of crystallographic visualisation across postwar British science and industrial design undertaken in this thesis has not been previously pursued. This research, however, demonstrates the value of exploring this interdisciplinary territory: it illuminates not only the history of exchange between crystallography and design in the past, but also generates new insights about the history of postwar British modernist design and the postwar history of X-ray crystallography. This research also yields methodological lessons for the history of science and design history. This study is rooted in specific questions, discourses and methodologies operating in these disciplines. But it also poses new questions, experiments with interdisciplinary approaches, and forges new relationships between them.

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[3] Elizabeth E. Guffey, *Retro: The Culture of Revival* (London: Reaktion, 2006).

Historiography and disciplines

In the sections below I introduce bodies of literature and concepts emanating from both design and science history that are relevant to this study. Further details of these historiographies appear in individual chapters as necessary, where such discussion is most productive. Additionally, many more discourses are pertinent to individual cases and are therefore introduced in the relevant chapters also. These include literature on craft, scientific representation, 'retro' consumption, public history and historiography on the FPG and ball-and-rod furnishings.

Throughout the chapters that follow, methods, scholarship and frameworks aligned with history of science and design history discourses intermingle and confront one another as is necessary to the thesis's explorations. Throughout much of this introduction however, literature and questions associated with each are considered separately, because research bridging the fields is limited. This leads to some natural asymmetries in their weight and representation here. Although this thesis is addressed to scholars in both fields, this introduction devotes more space to design history concepts and literature for two practical reasons. The first is that many of the questions about exchange between crystallography and design emanate from design history (as design historians have more frequently interpreted designed objects as being in some way related to science). Secondly, chapter one focuses on the history of X-ray crystallography, so given that detailed historiographical and background information on the subject appears very soon (in that chapter), its introduction here is more abbreviated.

The historiography of exchange between postwar British design and science

Although design history and the history of science as practiced today are both quite interdisciplinary fields, design history literature rarely engages deeply with scientific subjects, and vice versa[4]. A body of research touching on twentieth-century British X-ray crystallography and extensive scholarship on postwar British industrial design exist, split neatly between history of science and history of design disciplines respectively[5]. Scholarship considering both postwar British design and science, however, is rare. Exchange between the fields of X-ray crystallography and industrial design in postwar Britain has not been researched in depth beyond the context of the FPG (the literature on which, as I explain in chapter two, leaves room for further work).

In comparison to research considering postwar design within the context of contemporaneous scientific investigations of molecular and atomic structures (the subject of X-ray crystallography), there is greater interest among historians of postwar design and architecture in responses to the Cold War threat of nuclear science's destructive applications and the scientific development of new materials[6]. Even in these topic areas, however, research on the postwar British context is under-represented[7]. And given that the focus of such research is designed objects and spaces, scientific contexts are rarely foregrounded or examined in depth.

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[4] Both fields are interdisciplinary in now well-established ways, which include both disciplines' adoption of aspects of material culture studies from anthropology, and the history of science's exchange with science and technology studies (STS). There is also a growing interest in approaches aligned with STS, particularly actor-network theory, among design historians for understanding objects and technologies in the context of social interactions. This burgeoning disciplinary exchange was signalled by the 2008 Design History Society's invitation of sociologist of science and network theorist Bruno Latour as its keynote speaker. For an overview of overlaps between current interests in design history and STS and design historians' interest in STS, see Kjetil Fallan, 'Our Common Future: Joining Forces for Histories of Sustainable Design', *Tecnoscienza: Italian Journal of Science & Technology Studies*, 5 (2) (2014), 15-32.

[5] These are outlined later in this introduction and discussed further in individual chapters.

[6] Catherine Jolivette, 'Representations of Atomic Power at the Festival of Britain', in *British Art in the Nuclear Age*, ed. by Catherine Jolivette (Surrey: Ashgate, 2014), pp. 103-125; *Atomic Dwelling: Anxiety, Domesticity, and Postwar Architecture*, ed. by Robin Schuldenfrei (Oxon: Routledge, 2012); *Cold War Hothouses: Inventing Postwar Culture, From Cockpit to Playboy*, ed. by Beatriz Colomina, Annemarie Brennan and Jeannie Kim (New York: Princeton Architectural Press, 2012); Jane Pavitt, *Fear and Fashion in the Cold War* (London: V&A, 2008); *Cold War Modern: Design 1945-1970*, ed. by David Crowley and Jane Pavitt (London: V&A, 2008); Beatriz Colomina, *Domesticity at War* (Cambridge, Massachusetts: MIT, 2007); *Vital Forms: American Art and Design in the Atomic Age, 1940-1960*, ed. by Brooke Kamin Rapaport and Kevin L. Stayton (New York: Harry N. Abrams, 2001).

[7] Literature on British design in the nuclear context includes recent work by art historian Catherine Jolivette on the role of exhibition design in the Festival of Britain's presentations of nuclear science (Jolivette, 'Representations of Atomic Power'), and essays by Barry Curtis and Jane Pavitt in 2008's *Cold War Modern* touching on British responses to nuclear anxiety, primarily those of the artists, architects and designers associated with the Independent Group. Jane Pavitt, 'The Bomb in the Brain', in *Cold War Modern*, pp. 100-121; Barry Curtis, 'War Games: Cold War Britain in Film and Fiction', in *Cold War Modern*, pp. 122-127.

Most literature considering both postwar British science and design emanates from design history. The notion of period style, which approaches design history as a progression of styles aligned with particular eras, sets the tone for many design history texts (within and outside academic discourses) on postwar science-inflected objects. The intersection of postwar science and design is most heavily emphasised in accounts that read the history of postwar design (in US and European contexts) through surface observations of visual motifs and formal qualities found across period objects[8]. Many historical accounts published since the late 1970s describe the 'molecular' as one such generalised feature of postwar period style in British design tightly linked to the 1951 Festival (this is also repeated in histories of science providing background glosses on the influence of X-ray crystallography in postwar British culture)[9]. For example, design historian Jonathan Woodham writes:

> "Molecules" became a widespread ornamental trait in the early 1950s: in the feet of the increasingly ubiquitous plant pot holders or domestic appliances, in the decorative elements of balustrading and space dividers in public buildings and stores, or in other environmental features of everyday life[10].

There is an accepted narrative that forms associated with molecular representations, such as those produced by X-ray crystallographers, had a clear and direct influence on the forms and appearance of designed objects in postwar Britain. It is in this way that the FPG prototypes and ball-and-rod furnishings, while seeing little academic historical research, are nevertheless embedded in historical narratives. These narratives overwhelmingly assume an implied, undifferentiated, and unquestioned historical category of the 'molecular' in postwar British material culture linked to a notion of postwar period style[11].

An approach to design history as a succession of period styles has long been criticised and eschewed by academic design history because it excludes numerous social, material, political, cultural and other historical contingencies,

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[8] See for example *Vital Forms*; Lesley Jackson, *The New Look: Design in the Fifties* (London: Thames and Hudson, 1998).
[9] This literature is outlined in detail in the introduction to part two and in chapter three.
[10] Jonathan M. Woodham, *Twentieth-Century Ornament* (Studio Vista: London, 1990), p. 204.
[11] These narratives are reviewed in chapter two, concerning the FPG, and part two involves detailed discussion of such narratives particularly as they relate to ball-and-rod furnishings.

resulting in teleological narratives[12]. Academic design historians work with style differently, understanding it, as this research does, as one of many interwoven aspects of an object and its larger historical context, rather than the primary framing device for understanding an artefact. As this thesis demonstrates, close attention to material and visual decorative forms need not operate only at a surface level; ornamental style is interconnected with social and material practices and conditions (including the politics of taste, for example), and communication between fields or cultures.

A rich picture of X-ray crystallographic visualisations (or even a evidence-based understanding of the science) is missing from most narratives about transmission between X-ray crystallographic visualisation and industrial design in postwar Britain. Analyses of crystallographic visualisations' production and circulation, and discourses from science scholarship on scientific representation generally, have not been a part of existing studies pertaining to artefacts of postwar industrial design that historians associate with molecular and crystal structures. As this thesis demonstrates, however, investigations of the material production and use of models and diagrams by scientists, their circulation beyond the laboratory among networks of designers and artists, and their mediation in public display are necessary to understanding the history of exchange between postwar British industrial design and crystallography.

This thesis thus problematises the existing narratives of exchange between crystallography and design. It responds to the need for an examination of the designed objects under examination that moves beyond the concept of period style, and which is receptive to possible heterogeneity and aberration operating within and challenging the implicit historical category of postwar science-inflected design. To do so, it interrogates the under-explored mechanisms of transmission between crystallography and industrial design. This study investigates the details of production, circulation and reception of artefacts within a larger exploration of the shifting form, use and significance of X-ray crystallographic visualisation in postwar British material culture. The research

[12] This was a founding concern voiced by several design historians engaged in discussions about the character of the academic discipline of design history in the 1980s, when design history as a distinct academic field was relatively new. Clive Dilnot, 'The State of Design History, Part II: Problems and Possibilities', *Design Issues*, 1 (2) (1984), 3-20; Fran Hannah and Tim Putnam, 'Taking Stock in Design History', *Block*, 3 (1980), 25-34.

necessitated drawing on scholarship from outside the limited historiography on the topic of postwar British intersections of design and science. It incorporates perspectives from literature on scientific practice and representation. It draws upon history of design scholarship on postwar British modernism that understands 'design' not only as 'style', but as a subject matter embedded in multiple socially-situated practices and processes. And this research employs thinking on cultural transmission from studies of global exchange. These areas of scholarship are introduced below.

Crystallographic visualisation inside and outside the laboratory

This thesis explores postwar X-ray crystallographic visualisation in British material culture both in the scientific context and in its mediation, adaptations and associations within other cultural realms. In doing so, it pursues questions aligned with both the history of science and design history. In this section I introduce the literature and inquiries emanating from the history of science that are relevant to this study.

The models and diagrams discussed in this thesis fall generally within the category of scientific representation. This category includes images, diagrams, and models, the making, use and circulation of which, science scholars argue, contribute to the very act of scientific knowledge generation[13]. In this thesis, however, I use the term 'visualisation' to refer to crystallographic diagrams and models instead of 'representation'. This is because the latter carries connotations of realism that are inappropriate in this case. Crystallographic models and diagrams emanate from the interpretation of data, rather than naturalistic observation. Although representation does not necessarily refer to mimesis, as historian of science Lorraine Daston suggests, the 'specter of the perfect copy still haunts the history of science' when it comes to representation[14]. Postwar X-ray crystallography involved 'making visible' that which was otherwise

[13] The literature on scientific representation is outlined in chapter one.
[14] Lorraine Daston, 'Beyond Representation', in *Representation in Scientific Practice Revisited*, ed. by Catelijne Coopmans, Janet Vertesi, Michael Lynch, and Steve Woolgar (Cambridge, Massachusetts: MIT Press, 2014), pp. 319-322 (p. 319).

invisible[15]. Of course, postwar crystallographic diagrams and models, as physical objects, also made the scientists' subject matter tangible. The term 'visualisation' (which emphasises the visual) does not capture this aspect. This is a downside of its use and is not reflective of the perspectives of this research, in which the materiality of the objects studied is in fact crucial. The term is nevertheless the most expedient alternative to 'representation' (to pioneer a new usage of the word 'materialisation' would simply cause confusion).

Since the 1970s and 1980s sociologists in the field of science and technology studies (STS) and historians of science have acknowledged that science is not merely comprised of discoveries by individual figures. Social practices, including laboratory routines and the construction and manipulation of representations condition scientific knowledge generation[16]. A key aim of much science scholarship on representations is to understand their roles in knowledge generation and communication and how social factors shape these roles. Mid-twentieth-century X-ray crystallography and crystallographic visualisation, however, have received little in-depth attention under this science-as-practice framework. A key exception, which this thesis builds upon, is the research by historian of science Soraya de Chadarevian. She examines aspects of postwar protein crystallography in Cambridge within a larger study of postwar molecular biology[17]. Many historical texts on X-ray crystallography are accounts written by

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[15] Michelle G. Gibbons, 'Reassessing Discovery: Rosalind Franklin, Scientific Visualization, and the Structure of DNA', *Philosophy of Science*, 79 (1) (January 2012), 63-80 (p. 63).

[16] Key texts exploring science as a social practice include Karin Knorr Cetina, *Epistemic Cultures: How the Sciences Make Knowledge* (Cambridge, Massachusetts: Harvard University Press, 1999); Steven Shapin and Simon Schaffer, *Leviathan and the Air Pump: Hobbes, Boyle and the Experimental Life* (Princeton: Princeton University Press, 2011 [1985]); Bruno Latour and Steve Woolgar, *Laboratory Life: The Social Construction of Scientific Facts* (Princeton: Princeton University Press, 1986 [1979]); Thomas S. Kuhn, *The Structure of Scientific Revolutions* (Chicago: University of Chicago, 1970 [1962]). Chapter one contains a more detailed review of literature on representations in scientific practice.

[17] Soraya de Chadarevian, 'Models and the Making of Molecular Biology', in *Models: The Third Dimension of Science*, ed. by Soraya de Chadarevian and Nick Hopwood (Stanford: Stanford University Press, 2004), pp. 339-368; Soraya de Chadarevian, *Designs For Life: Molecular Biology after World War II* (Cambridge: Cambridge University Press, 2002). A number of smaller studies touch on discrete aspects of instrumentation, social life or institutional themes having to do with X-ray crystallography or specific X-ray crystallographers. These include Michelle G. Gibbons, 'Reassessing Discovery'; Melinda Baldwin, ''Where Are Your Intelligent Mothers To Come From?': Marriage and Family in the Career of Kathleen Lonsdale FRS', *Notes and Records of the Royal Society*, 63 (2009), 81–94; Robin Wolfe Scheffler, 'Interests and Instrument: A Micro-History of Object Wh.3469 (X-ray Powder Diffraction Camera, ca. 1940)', *Studies in History and Philosophy of Science*, 40 (2009), 396-404; Angela N. H. Creager and Gregory J. Morgan, 'After the Double Helix: Rosalind Franklin's Research on Tobacco Mosaic

the scientists themselves[18], and biographies of crystallographers[19], rather than texts wholly embedded in academic history of science research. Consequently, this thesis, which opens in chapter one with an exploration of crystallographic practices of visualisation, and material and social contingencies operating therein, contributes new evidence-based information on such practices to the history of this field.

The exploration of X-ray crystallographic visualisation in this thesis differs, however, from most studies of scientific representation and practice in the history of science. This is firstly, because it applies specific disciplinary methods across discipline boundaries: I will propose perspectives on craft from design history scholarship as a tool for studying scientific objects. Secondly, in addition to contributing to the history of X-ray crystallography, my examination of crystallographic visualisation also feeds into discussions of design.

Scientific representations operate not only within the laboratory and scientific community, but also in forums beyond scientific research, as historians

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Virus', *Isis*, 99 (2) (June 2008), 239-272; John Agar, 'What Difference Did Computers Make?', *Social Studies of Science*, 36 (6) (2006), 869-907; Jeff Hughes, 'Craftsmanship and Social Service', in *'The Common Purposes of Life': Science and Society at the Royal Institution of Great Britain*, ed. by Frank A. J. L. James (Aldershot: Ashgate, 2002), pp. 224–247; Peter J.T. Morris and Anthony Travis, 'The Role of Physical Instrumentation in Structural Organic Chemistry in the Twentieth Century', in *From Classical to Modern Chemistry: The Instrumental Revolution*, ed. by Peter J.T. Morris (Cambridge: Royal Society of Chemistry, 2002), pp. 57-84; Robert Olby, *The Path to the Double Helix: The Discovery of DNA* (New York: Dover, 1974); John Law, 'The Development of Specialties in Science: The Case of X-ray Protein Crystallography', *Science Studies*, 3 (3) (1973), 275-303.

[18] André Authier, *Early Days of X-ray Crystallography* (Oxford: Oxford University Press, 2013); U. W. Arndt, 'Instrumentation in X-ray Crystallography: Past, Present and Future', *Notes and Records of the Royal Society of London*, 55 (3) (2001), 457-472; *Historical Atlas of Crystallography*, ed. by J. Lima-de-Faria (Dordrecht: Kluwer Academic, 1990); Lawrence Bragg, *The Development of X-ray Analysis*, ed. by D.C. Phillips and H. Lipson (New York: Dover, 1992 [1975]); James D. Watson, *The Double Helix: A Personal Account of the Discovery of the Structure of DNA* (London: Weidenfeld and Nicolson, 1997 [1968]); *Fifty Years of X-ray Diffraction*, ed. by Paul Peter Ewald (Utrecht: Oosthoek, 1962).

[19] Kersten T. Hall, *The Man in the Monkeynut Coat: William Astbury and the Forgotten Road to the Double Helix* (Oxford: Oxford University Press, 2014); Jenifer Glynn, *My Sister Rosalind Franklin* (Oxford: Oxford University Press, 2012); John Jenkin, *William and Lawrence Bragg, Father and Son: The Most Extraordinary Collaboration in Science* (Oxford: Oxford University Press, 2008); Georgina Ferry, *Perutz and the Secret of Life* (London: Chatto & Windus, 2007); Andrew Brown, *J.D. Bernal: The Sage of Science* (Oxford: Oxford University, 2005); Graeme K. Hunter, *Light Is a Messenger: The Life and Science of William Lawrence Bragg* (Oxford: Oxford University, 2004); Brenda Maddox, *Rosalind Franklin: The Dark Lady of DNA* (London: Harper Collins, 2002); *J.D. Bernal: A Life in Science and Politics*, ed. by Brenda Swann and Francis Aprahamian (London: Verso, 1999); Georgina Ferry, *Dorothy Hodgkin: A Life* (London: Granta Books, 1998); Maurice Goldsmith, *Sage: A Life of J.D. Bernal* (London: Hutchinson, 1980); Anne Sayre, *Rosalind Franklin and DNA* (New York: Norton Press, 1975).

of science exploring their public display have established[20]. This research examines the circulation of crystallographic visualisations among figures in design and art fields, and their broader circulation through public display. It therefore reflects on questions asked within a research area in the history of science concerned with what is sometimes termed 'science in culture'[21]. Such research studies the modes and discourses of the circulation of scientific knowledge among publics outside scientific elites, its reception and negotiation, and relationships between scientific experts and other publics[22]. The term 'science in culture' is not ideal; as historian of science Sophie Forgan has pointed out, it presupposes a stark separation between 'science' and 'culture'[23]. But it is nevertheless a useful terminology here for describing historical investigations of science in publics or culture*s* outside of that of scientific practice (which as I explain below is also a 'culture').

There is a growing literature on science in postwar British culture, specifically focusing on science television, exhibitions, film and textual media[24].

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[20] James A. Secord, 'Monsters at the Crystal Palace', in *Models: The Third Dimension of Science*, pp. 138-169; Christoph Meinel, 'Molecules and Croquet Balls', in *Models: The Third Dimension of Science*, pp. 242-274; de Chadarevian, 'Models and the Making of Molecular Biology'; de Chadarevian, *Designs For Life*.

[21] This general topic area also goes by other labels such as 'science and popular culture' (depending on the forms of cultural production investigated) and 'science in public', and might include forms of 'science popularisation' and studies of the 'public understanding of science'.

[22] Key texts in this area include Katy Price, *Loving Faster Than Light: Romance and Readers in Einstein's Universe* (Chicago: University of Chicago Press, 2012); Katherine Pandora and Karen A. Rader, 'Science in the Everyday World', *Isis*, 99 (2) (June 2008), 350-364; Peter J. Bowler, *Science for All: The Popularization of Science in Early Twentieth-century Britain* (Chicago: University of Chicago Press, 2007); Bernard Lightman, *Victorian Popularizers of Science: Designing Nature for New Audiences* (Chicago: Chicago University Press, 2007); Aileen Fyfe, *Science and Salvation: Evangelical Popular Science Publishing in Victorian Britain* (Chicago: Chicago University Press, 2004); James A. Secord, 'Knowledge in Transit', *Isis*, 95 (2004), 654–672; James A. Secord, *Victorian Sensation: The Extraordinary Publication, Reception, and Secret Authorship of Vestiges of the Natural History of Creation* (Chicago : University of Chicago Press, 2000); Jane Gregory and Steve Miller, *Science in Public: Communication, Culture, and Credibility* (London: Plenum Trade, 1998); Gillian Beer, *Open Fields*: *Science in Cultural Encounter* (Oxford: Oxford University Press, 1996); Roger Cooter and Stephen Pumfrey, 'Separate Spheres and Public Places: Reflections on the History of Science Popularization and Science in Popular Culture', *History of Science*, 32 (1994), 237–267. See also the 2009 special issue of *Isis* on 'popular science': *Isis*, 100 (2) (June 2009). Further sources on science in culture in the postwar British context specifically are noted below.

[23] Sophie Forgan, 'Festivals of Science and the Two Cultures: Science, Design and Display in the Festival of Britain, 1951', *The British Journal for the History of Science*, 31 (2) (1998), 217-240 (p. 218).

[24] Timothy Boon and Jean-Baptiste Gouyon, 'The Origins and Practice of Science on British Television', in *The Routledge Companion to British Media History*, ed. by Martin Conboy and John Steel (Oxon: Routledge, 2015), pp. 470-483; Timothy Boon, ''The Televising of Science is a Process of Television': Establishing *Horizon*, 1962-1967', *The British Journal for the History of Science*, 48 (2015), 87-121; Jolivette; Richard Hornsey, ''Everything is Made Of Atoms': The

This includes a large body of research devoted to British 'nuclear culture', which includes scholarship on relationships between nuclear science and various publics through politics, the media, film, literature and several forms of cultural production[25]. Yet the topic of X-ray crystallography and molecular representations in public in postwar British culture is an under-researched area. It is covered at any significant length only in de Chadarevian's descriptions of some aspects of X-ray crystallography's coverage on television within her work on molecular biology, and in limited research on the FPG[26].

This thesis explores aspects of the circulation of X-ray crystallography visualisations in public forums such as television and exhibitions. I investigate these instances of display as possible channels through which knowledge in the form of a model, diagram or visualisation convention might flow between cultures – from scientific to design fields and to the wider public. The public display of X-ray crystallographic visualisation is not a pronounced focus of this thesis, however, because such public display was found to be of limited relevance to the questions about the life of crystallographic visualisations outside the laboratory pursued here. More important to this study is the circulation of visualisations among more discrete networks of art and design figures in postwar Britain. Additionally, I will point to design, and science-inflected ornament in particular, as future subject areas for interdisciplinary studies of science in

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Reprogramming of Space and Time in Post-War London', *Journal of Historical Geography*, 34 (2008), 94-117; Tim Boon, *Films of Fact: A History of Science in Documentary Films and Television* (London: Wallflower, 2007); Martin W. Bauer and Jane Gregory, 'From Journalism to Corporate Communication in Post-War Britain,' in *Journalism, Science and Society: Science Communication Between News and Public Relations*, ed. by Martin W. Bauer and Massimiano Bucchi (London: Routledge, 2007), pp. 33–51; Sophie Forgan, 'Atoms in Wonderland', *History and Technology*, 19 (3) (2003), 177-196; Robert Jones, '"Why Can't You Scientists Leave Things Alone?" Science Questioned in British films of the Post-War Period (1945–1970)', *Public Understanding of Science*, 10 (2001), 365-382; Forgan, 'Festivals of Science'.

[25] On the historical discourse on British 'nuclear culture' see Jonathan Hogg and Christoph Laucht's introduction to the December 2012 special issue of the *British Journal for the History of Science* on 'nuclear culture', and Jeff Hughes' critical appraisal of 'British nuclear culture' as a historical category in the same issue. Jonathan Hogg and Christoph Laucht, 'Introduction: British Nuclear Culture', *British Journal for the History of Science*, 45 (4) (2012), 479-493; Jeff Hughes, 'What is British Nuclear Culture? Understanding Uranium 235', *British Journal for the History of Science*, 45 (4) (2012), 495–518. See also Kirk Willis, 'The Origins of British Nuclear Culture, 1895–1939', *Journal of British Studies*, 34 (1995), pp. 59–89.

[26] Lesley Jackson, *From Atoms to Patterns: Crystal Structure Designs from the 1951 Festival of Britain* (Somerset: Richard Dennis, 2008); Chadarevian, *Designs For life*; 'Models and the Making of Molecular Biology'; Forgan, 'Festivals of Science'.

culture; this research identifies both designers and consumers of science-inflected ornament as potential publics for science[27].

A place for the molecular in the historiography on postwar British design

The designed objects examined in this thesis are part of the history of postwar British modernist industrial design. But they have largely escaped significant consideration within recent empirical research in academic design history on the topic. This thesis reveals their nuanced relationships to modernist practices, ideologies and - in the case of ball-and-rod objects – their position within the consumption of postwar British modernist design.

Themes related to modernism arise throughout this thesis, so I will introduce its general contours, and the perspectives from which historians have studied postwar British modernist design. The significance of the term ‘modernism’ varies across the myriad cases to which it has been applied in design contexts, making it notoriously difficult to define. The ‘continental modern movement’ refers here to a set of ideas, and the aesthetic or material approaches that came to stand for those ideas, that developed in continental European architecture and design circles beginning in the 1910s in response to the material and social conditions of industrialised modernity[28]. It is generally characterised by an impulse to change (or, ostensibly, to improve) everyday living conditions, a positivistic belief in progress, and a conviction that social reform can be achieved through design. Many modernist practices and theories in this context embraced standardised, mass production methods (at least in theory if rarely in practice in this early period), and industrial materials[29].

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[27] Currently, the limited considerations of design in studies of science in culture focus primarily on the exhibition design of science exhibitions. Discussions of these science exhibitions, however, do not engage deeply with the context of design practice relevant to their production or with the reception of such exhibition design. Most texts in this area concern displays of nuclear physics at the Festival of Britain. Jolivette; Hornsey; Forgan, ‘Atoms in Wonderland’; Forgan, ‘Festivals of Science’.

[28] It is easy to present this collection of practices, ideas, objects and spaces as more cohesive than it actually was. My purpose in singling out and defining the continental modern movement is primarily to distinguish it from British modernism, which was in many ways defined in relationship to the ideals of continental modernism developed in the early decades of the twentieth century enumerated here (and what British modernists perceived those of continental modernism to be).

[29] *Modernism: Designing a New World, 1914-1939*, ed. by Christopher Wilk (London: V&A, 2008); *Modernism in Design*, ed. by Paul Greenhalgh (London: Reaktion, 1990).

The impulse to effect social change through design saw moral and aesthetic values merged, particularly on the subject of ornament, toward which many modernist theorists expressed suspicion. For example, Austrian architect Adolf Loos, in his 1908 essay 'Ornament and Crime', famously classed ornament as degenerate. '*The evolution of culture is synonymous with the removal of ornament from utilitarian objects*', he wrote[30]. This is not to say however that modernist designers eschewed all decoration. Despite the rhetoric of 'form follows function' associated with modernism, many modernist objects and spaces evidence stylistic features generated outside the imperatives of function[31].

Ideals and aesthetic attributes associated with the continental modern movement as defined above gained significant momentum in British design circles in the 1920s and 1930s. British modernist critics such as Herbert Read and John Gloag were galvanised in the 1930s by the German émigré historian Nikolaus Pevsner, whose celebratory *Pioneers of the Modern Movement* (1936) presented a teleological 'evolution' of design leading to the modern movement[32]. At this point, however, the material presence of modernist design in Britain was limited. The few firms producing modernist furniture, for example, served a limited and rarified middle-class market[33].

British modernists shared a social reformist impulse and, to a degree, anti-ornament stance with the continental modern movement[34]. They hoped to alter the taste and everyday living environments of the population through modernist design and to steer British design away from the heavy ornamentation

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[30] Adolf Loos, 'Ornament and Crime', in *The Theory of Decorative Art*, ed. by Isabelle Frank (New Haven: Yale University, 2000), pp. 288-294 (p. 289).
[31] *Modernism in Design*, p. 41.
[32] Nikolaus Pevsner, *Pioneers of Modern Design* (London: Yale University Press, 2005 [1936]), p. 20; Fiona MacCarthy, *A History of British Design, 1830-1970* (London: George Allen & Unwin Ltd, 1979).
[33] Kevin Davies, 'Scandinavian Furniture in Britain: Finmar and the UK Market, 1949-1952', *Journal of Design History*, 10 (1) (1997), 39-52; Barbie Campbell-Cole, 'The Arrival of Tubular Steel Furniture in Britain', in *Tubular Steel Furniture*, ed. by Barbie Campbell-Cole and Tim Benton (London: The Art Book Company, 1979), pp. 52-67; Penny Sparke, *Furniture* (London: Bell & Hyman Ltd, 1986).
[34] Judy Attfield, *Bringing Modernity Home: Writings on Popular Design and Material Culture* (Manchester: Manchester University Press, 2007); *Utility Reassessed: The Role of Ethics in the Practice of Design*, ed. by Judy Attfield (Manchester: Manchester University, 1999); Harriet Dover, *Home Front Furniture: British Utility Design 1941-1951* (Aldershot: Scolar Press, 1991).

of Victorian furniture[35]. However, most British modernists, before and after the war, were critical of the functional ethic and aesthetic (or 'functionalism') they ascribed to continental modernist practices, such as that of the architect Le Corbusier and those associated with the Bauhaus, on the grounds that their designs involved an inhuman degree of mechanisation[36]. 'Functionalism in industry', Read wrote, 'is the exact contrary of humanism. Its final effect is to eliminate the human element from production'[37].

The aspirations of British modernist design reformers were enshrined in official policy during and after the Second World War when reformers assumed positions in the wartime Utility scheme and the CoID, and proposed their vision of design in response to the social and economic challenges engendered by the war[38]. The notion of 'good design' shaped much postwar design policy. 'Good design' evidenced modernist tenets of functionality and standardisation in industrially-produced designed objects, alongside the valorisation of craftsmanship and a 'truth to materials' approach of the nineteenth-century British Arts and Crafts Movement[39].

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[35] The development of British modernist design reformers' ideals in the first half of the twentieth century can be traced in part through the activities of the Design And Industries Association (DIA). The DIA, established in 1915, was modelled on the German Werkbund (an association bringing together modern industry and craft), and looked to the nineteenth-century Arts and Crafts movement (which responded to the industrialisation of production by advocating a return to handcraft), although members of the DIA did not share the eschewal of industrial production associated with the Arts and Crafts movement. Cheryl Buckley, *Designing Modern Britain* (London: Reaktion, 2007); MacCarthy.

[36] Tim Benton, 'The Myth of Function', in *Modernism in Design*, pp. 41-52; Nigel Whiteley, *Pop Design: Modernism to Mod* (London: The Design Council, 1987); MacCarthy.

[37] Herbert Read, *Art and Industry* (London: Faber and Faber, 1966 [1934]), p.14.

[38] The Utility furniture scheme (1942-52) was a government effort to manage scarce resources so that furniture could be produced and distributed efficiently to citizens in need. Constructed primarily of wooden frames and hardboard panels, Utility furniture was designed to be economical to produce, and also pointedly eschewed the heavy ornamentation of popular styles at the time such as reproduction Jacobean furniture, which ran counter to the tastes of modernist design reformers such as the Utility furniture scheme's director Gordon Russell. Attfield, *Bringing Modernity Home*; *Utility Reassessed*.

[39] On the CoID's promotion of 'good design' in postwar Britain, see Christine Atha, 'Dirt and Disorder: Taste and Anxiety in the Homes of the British Working Class', in *Atomic Dwelling*, pp. 207-226; Buckley; Lesley Whitworth, 'Anticipating Affluence: Skill, Judgement and the Problems of Aesthetic Tutelage', in *An Affluent Society?: Britain's Post-War 'Golden Age' Revisited*, ed. by Lawrence Black and High Pemberton (Aldershot: Ashgate, 2004), pp. 167-183; Michelle Jones, 'Design and the Domestic Persuader: Television and the British Broadcasting Corporation's Promotion of Post-war 'Good Design'', *Journal of Design History*, 16 (4) (2003), 307-318; Stephen Hayward, ''Good Design is Largely a Matter of Common Sense': Questioning the Meaning and Ownership of a Twentieth-Century Orthodoxy', *Journal of Design History*, 11 (3) (1998), 217-233; *Design and Cultural Politics in Postwar Britain: The Britain Can Make It Exhibition of 1946*, ed. by Patrick J. Maguire and Jonathan M. Woodham (London: Leicester University Press, 1997); Jonathan M. Woodham, 'Managing British Design Reform I: Fresh

Before the so-called 'popular turn' in academic design history in the 1990s, design histories of post-war Britain displayed a narrow focus on the products of celebrated, canonical modernist designers, continuing a tradition reaching back to Pevsner's *Pioneers of the Modern Movement*[40]. This limiting 'modernist' mode of design history-writing was also a product of the origins of the discipline as a contextual studies component of UK design practice degree courses. Design historian Grace Lees-Maffei explains that this original production-focus necessarily reflected 'the taste among students, as emergent designers, for information about the careers of successful practitioners and companies, from which they hope to find exemplars'[41].

Until now, the designed objects studied in this thesis have rarely been considered outside the frames of modernist design history writing. The analyses here therefore aim to bring these topics into the domain of contemporary design history discourse, which is shaped by different approaches. This study is influenced by accounts published since the 1990s in which design historians ask different questions about British modernist design. These concern the mediation of modernist design (a research area that is somewhat limited to a focus on the CoID), its consumption in the period, and the class and gender politics through which the consumption and promotion of modernist design were inflected[42]. By

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Perspectives on the Early Years of the Council of Industrial Design', *Journal of Design History*, 9 (1) (1996), 55-65; Jonathan M. Woodham, 'Managing British Design Reform II: The Film "Deadly Lampshade": An Ill-fated Episode in the Politics of 'Good Taste'', *Journal of Design History*, 9 (2) (1996), 101-115; *Utility Reassessed*; Attfield, *Bringing Modernity Home*; *Did Britain Make It?: British Design in Context 1946-86*, ed. by Penny Sparke, (London: The Design Council, 1986); Gordon Russell, *Designer's Trade: The Autobiography of Gordon Russell* (London: Allen & Unwin, 1968).

[40] On the history of this modernist production-focus in the discipline, see Kjetil Fallan, *Design History: Understanding Theory and Method* (London: Bloomsbury, 2013); Grace Lees-Maffei, 'The Production – Consumption – Mediation Paradigm', *Journal of Design History*, 22 (4) (2009), 351-376; *Utility Reassessed*. Early on in the development of design history as an academic discipline, design historians Fran Hannah and Tim Putnam critiqued the emphasis on the individual 'named' designer as a kind of 'artist-hero', arguing that it often misrepresents the history of a particular type of designed object, omitting discussion of social factors outside of (and acting on) the agency of a single designer. Hannah and Putnam, p. 25.

[41] Lees-Maffei, 'The Production – Consumption – Mediation Paradigm', p. 355.

[42] Attfield, *Bringing Modernity Home*; Grace Lees-Maffei, 'From Service to Self-Service: Advice Literature as Design Discourse, 1920-1970', *Journal of Design History*, 14 (3) (2001), 187-206; David Jeremiah, *Architecture and Design for the Family in Britain, 1900-70* (Manchester: Manchester University Press, 2000); Stephen Hayward, ''Good Design is Largely a Matter of Common Sense'; *Design and Cultural Politics in Postwar Britain*; Davies, 'Scandinavian Furniture in Britain'; Woodham, 'Managing British Design Reform I'; Woodham, 'Managing British Design Reform II'; Judy Attfield, ''Give 'em Something Dark and Heavy': The Role of Design in the Material Culture of Popular British Furniture, 1939-1965', *Journal of Design*

'mediation' I refer to the sphere of what Lees-Maffei calls 'mediating channels' between producers and consumers, including advertisements, exhibitions, advice literature, and retailing[43]. These research areas reflect the expansion of the purview of design history research generally since the 1990s to encompass the consumption and mediation of designed objects.

This thesis contributes to the project represented by the above research strands. It offers a new angle on many of these topics due to the interdisciplinary perspective of this research. My investigation of the role of crystallographic visualisation in postwar British modernist design through studies of the FPG and ball-and-rod objects shows where practices, aesthetic ideologies, material conditions and the mediation, consumption and use of designed objects did – and did not – bring them into encounter. This thesis also examines modernist design from the angle of social, ideological and material conditions of production, as distinct from the 'artist-hero' mould of modernist accounts.

Questions about aesthetic ideologies operating in postwar British modernist design are important to this study because the associations of FPG objects and ball-and-rod furnishings with science emerge, at least at first glance, on the level of decorative features: a textile pattern based on the atomic structure of clay, for example, or the inclusion of red balls at the base of a magazine rack. Design historians have researched the character of modernist ideological and aesthetic frameworks operating in postwar Britain, several of which touch on postwar debates about ornament in design[44]. This thesis brings such research to

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History, 9 (3) (1996), 185-201; Penny Sparke, *As Long As It's Pink: The Sexual Politics of Taste* (London, Pandora: 1995); Julian Holder, ''Design in Everyday Things': Promoting Modernism in Britain, 1912-1944', in *Modernism in Design*, pp. 124-143; Whiteley, *Pop Design*; Catherine McDermott, 'Popular Taste and the Campaign for Contemporary Design in the 1950s', in *Did Britain Make It?*, pp. 156-164; Jonathan M. Woodham, 'Design Promotion 1946 and After', in *Did Britain Make It?*, pp. 23-37; Attfield, *Utility Reassessed*.

[43] Lees-Maffei, 'The Production – Consumption – Mediation Paradigm', p. 354.

[44] Glenn Hooper, 'English Modern: John Gloag and the Challenge of Design', *Journal of Design History*, 2015 [published online 25 May 2015], 1-17; Woodham, 'Managing British Design Reform I'; Woodham, 'Managing British Design Reform II'; Sparke, *Furniture*. I use the term 'ornament' in the broad sense described by design historian David Brett as 'applied decoration', the latter referring to 'a family of practices devoted to visual pleasure'. Historians sometimes distinguish between ornament and pattern on the grounds that ornament is applied after-the-fact to a functional entity, whereas pattern is embedded in it, but even here modernist ideology permeates the terminology, so such distinctions are not relevant to my general use of the terms. See, for example, *Patterns in Design, Art and Architecture*, ed. by Petra Schmidt, Annette Tietenberg, Ralf Wollheim (Basel: Birkhäuser, 2005). David Brett, *Rethinking Decoration: Pleasure and Ideology in the Visual Arts* (Cambridge: Cambridge University Press, 2005), p. 4.

bear on analyses of the designed objects studied in this thesis, which have so far not been considered in relation to this scholarship.

Cultural transmission

'Cultural transmission' is a concept central to my analyses of the transmissions, translations, associations, disjuncture and communication between postwar X-ray crystallography and industrial design. I have adapted the concept from studies of global exchange carried out within design history, transnational histories of science and technology, cultural studies, anthropology and global history[45]. Such research focuses on the transmission or translation of knowledge, objects, imagery, practices, texts, people and much more between cultures through mechanisms such as communication through personal networks, media technologies or the circulation and consumption of objects[46]. In this thesis, the cultures under consideration are primarily the professional contexts of postwar British X-ray crystallography and industrial design.

Cultural transmission is an apt framing device for explorations of cross-field exchange. The concept is associated with questions about mechanisms of

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[45] Although I draw upon an interdisciplinary body of scholarship on cultural transmission, there is a degree of emphasis on design histories of global exchange because they more frequently contend with the cultural transmission and translations of objects, ornamental styles and knowledge concerning their production, and with questions of consumption. These themes are central to this research.

[46] Key texts include: D. J. Huppatz, 'Globalizing Design History and Global Design History', *Journal of Design History*, 28 (2) (2015), 182-202; Christine Guth, *Hokusai's Great Wave: Biography of a Global Icon* (Honolulu: University of Hawai'i Press, 2015); Helena Čapková, 'Transnational Networkers—Iwao and Michiko Yamawaki and the Formation of Japanese Modernist Design', *Journal of Design History*, 27 (4) (2014), 370-385; Simone Turchetti, Néstor Herran and Soraya Boudia, 'Introduction: Have We Ever Been 'Transnational'? Towards A History Of Science Across and Beyond Borders', *British Journal for the History of Science*, 45 (3) (September 2012), 319–336; *Global Design History*, ed. by Glenn Adamson, Giorgio Riello and Sarah Teasley (New York: Routledge, 2011); Katerina Rüedi, *Bauhaus Dream-House: Modernity and Globalization* (Abingdon: Routledge 2010); Kapil Raj, *Relocating Modern Science: Circulation and the Construction of Knowledge in South Asia and Europe, 1650-1900* (Basingstoke: Palgrave Macmillan, 2007); Arindam Dutta, *The Bureaucracy of Beauty: Design in the Age of its Global Reproducibility* (Abingdon: Routledge 2007); David Edgerton, *The Shock of the Old: Technology and Global History Since 1900* (London: Profile Books, 2006); Joseph Needham, *The Grand Titration: Science and Society in East and West* (Abingdon: Routledge, 2005 [1969]); Christopher Bailey, 'The Global Future of Design History', *Journal of Design History*, 18 (4) (2005), 231-233; James Clifford, *Routes: Travel and Translation in the Late Twentieth Century* (Cambridge, Massachusetts: Harvard University Press, 1997); Arjun Appadurai, *Modernity at Large: Cultural Dimensions of Globalization* (Minneapolis: University of Minnesota Press, 1996); *Cross-cultural Consumption: Global Markets, Local Realities*, ed. by David Howes (London: Routledge, 1996); Homi K. Bhabha, *The Location of Culture* (Oxon: Routledge, 1994).

transmission and their ramifications for how we might think about relationships across cultures that correspond to those asked about crystallography and industrial design in this thesis. In *Global Design History*, Sarah Teasley, Giorgio Riello and Glenn Adamson describe a ''centre-less logic' for design history', which I contend also represents a fruitful direction for studying exchange between science and design. Teasley, Riello and Adamson highlight the researcher's act of tracing

> the interactive movement of things and ideas, and the processes of cross-fertilisation of taste. One might think about the different meanings assumed by a specific object when moving across cultures [...] connections often happen in an unstructured manner. They are affected by material and social conditions - a hill is easier to cross than a lake, and a friendly government is preferable to an enemy one[47].

Studies of cultural transmission contend with issues of translation across boundaries, the factors that foster or obstruct it, and the complex directionalities or a/symmetries of 'flows' that might characterise cultural exchange[48]. These also arise when we study exchange between science and design fields.

This thesis actively overturns a way of thinking about cultural transmission between postwar British crystallography and industrial design dictated by an 'influence' model in which 'design' reflects 'science', implying a clear, unilateral trajectory of knowledge, objects or images from one to the other. This model is most closely associated with writing about art. Art historian Michael Baxandall called the concept of 'influence' a 'curse of art criticism', because it 'beg[s] the question of cause without quite appearing to do so', and implies a particular attribution of agency[49]. Baxandall explains, 'If one says that X influenced Y it does seem that one is saying that X did something to Y rather

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[47] Sarah Teasley, Giorgio Riello and Glenn Adamson, 'Introduction: Towards Global Design History', in *Global Design History*, pp. 1-10 (p. 4).

[48] The concept of 'flows' comes from anthropologist Arjun Appadurai's exploration of what he terms 'global flows', which comprise movements of people, capital, technologies, and images through channels that he calls 'ethnoscapes, technoscapes, financescapes, mediascapes, and ideoscapes' in the conditions of globalization (in the late twentieth century, when he was writing). The term 'flow' is often used in the literature on cultural transmission more broadly however to describe movements of other things as well. Appadurai, *Modernity at Large*, p. 37.

[49] Michael Baxandall, *Patterns of Intention: On the Historical Explanation of Pictures* (New Haven: Yale Univeristy Press, 1985), p. 58-9.

than that Y did something to X'[50]. The situation is the reverse in this case, but it is no less asymmetric; existing narratives place agency with 'design', which takes influence from 'science', envisioned merely as the source of unadulterated forms that are acted upon by designers. This thesis reveals a more complex picture of agency in the scientific and design practices operating in the cases here.

The word 'culture', as used in this thesis to describe X-ray crystallography and industrial design in discussions of cultural transmission, refers to the social conditions, personal networks, debates, ideas and practices that defined the fields[51]. It is not suggestive of a deep cultural divide along the lines of the oft-mentioned 'two cultures' concept introduced in a lecture by the chemist and novelist C.P. Snow in 1959 to discuss disciplinary relationships between literary intellectuals and scientists[52]. Key to the analyses in this thesis is a notion of 'culture' as internally various and dynamic, and affected by 'contact zones' or 'trading zones' with other cultures[53].

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[50] Baxandall, *Patterns of Intention*, p. 59.

[51] On this concept of 'culture' see for example sociologist of science Karin Knorr Cetina who describes scientific cultures as constituted of the socially contingent 'patterns and dynamics that are on display in expert practice'. Cetina, p. 8.

[52] Although the 'two cultures' concept is often invoked today as a reflection of the postwar period, its usage as such frequently misrepresents its resonance in or correspondence to general facts about cultural rifts in the period, as historians Guy Ortolano and David Edgerton have established. Guy Ortolano, *The Two Cultures Controversy: Science, Literature and Cultural Politics in Postwar Britain* (Cambridge: Cambridge University Press, 2009); David Edgerton, *Warfare State: Britain 1920-1970* (Cambridge: Cambridge University Press, 2006).

[53] Literary scholar Mary Louise Pratt describes cultural 'contact zones' as points of interaction and exchange between cultures in which complex dynamics of agency and power play out. Contact zones, she writes, are 'social spaces where disparate cultures meet, clash, and grapple with each other, often in highly asymmetrical relations of domination and subordination – such as colonialism and slavery, or their aftermaths as they are lived out across the globe today'. This is similar to the concept of the 'trading zone' advanced by historians of science Peter Galison and Pamela O. Long. Long's use of this concept in particular shows its significance for understanding exchange between scientific cultures and others, as she describes trading zones where 'unskilled learned and skilled practitioners' in early modern Europe exchanged knowledge 'concerning material production and problems in engineering, but also concerning the nature of materials and of natural phenomena – traditionally topics belonging to natural philosophy'. She draws on Galison's research on 'trading zones' between subcultures within physics. Pamela O. Long, *Artisan Practitioners and the Rise of the New Sciences, 1400-1600* (Corvallis: Oregon State University, 2011), p. 8; Mary Louise Pratt, *Imperial Eyes: Travel Writing and Transculturation* (New York: Routledge, 2008 [1992]) p. 7; Peter Galison, *Image and Logic: A Material Culture of Microphysics* (Chicago: University of Chicago Press, 1997), p. xxi.

Methodology and sources

The originality of this research lies in part in its development of methods for examining cross-field relationships in the past, and for studying artefacts that move across the conventional boundaries of the history of science and history of design. This research draws upon an interdisciplinary set of approaches from both histories of design and science, including those derived from anthropology and STS. The principal aspects of my approach represent four areas of overlap between approaches used in history of science and history of design research: a focus on material culture, the use of network models, an emphasis on practices and the writing of object biographies. This section outlines the basic ideas underpinning the methodological arrangements in the thesis (the particular methodology necessitated by each case is described in each chapter).

Material culture studies have their roots in archaeology and anthropology research that treats objects as data, as evidence about the past[54]. Today, investigations of material culture rest on the notion that, as archaeologist Christopher Tilley writes, 'materiality is an integral dimension of culture'[55]. Historians of science and design examining material culture configured in this way pursue questions about relationships between materiality and/or objects and the culture and social life in which they are embedded[56]. This emphasis has increased with the recent 'object turn' in the humanities[57]. The focus on artefacts

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[54] Jules David Prown, 'Mind in Matter: An Introduction to Material Culture Theory and Method', *Winterthur Portfolio*, 17 (1) (Spring 1982), 1-19.
[55] *Handbook of Material Culture*, ed. by Christopher Tilley and others (London: Sage, 2006), p. 1. See also Daniel Miller, *Materiality* (Durham: Duke University Press, 2005); Victor Buchli, *Material Culture Reader* (Oxford: Berg, 2002); P.M. Graves-Brown, *Matter, Materiality and Modern Culture* (London: Routledge, 2000).
[56] Relevant texts in the history of science include Steven Shapin and Simon Schaffer, *Leviathan and the Air Pump*; *Things That Talk: Object Lessons from Art and Science*, ed. by Lorraine Daston (New York: Zone Books, 2008); Peter Galison, *Image and Logic*, as well as the scholarship on three-dimensional models detailed in chapter one. Key history of design texts explicitly encountering material culture (many more implicitly practice design history in a material culture-influenced framework) include Fallan, 'Our Common Future'; Fallan, *Design History*; Attfield, *Bringing Modernity Home*; Judy Attfield, *Wild Things: The Material Culture of Everyday Life* (Oxford: Berg 2000); Judy Attfield, 'Beyond the Pale: Reviewing the Relationship between Material Culture and Design History', *Journal of Design History*, 12 (4) (1999), 373-380; *The Gendered Object*, ed. by Pat Kirkham (Manchester: Manchester University Press, 1996).
[57] In an early influential text in this area, literature professor Bill Brown called for encounters with what he called 'the thingness of objects', in contrast to the tendency to only 'look through objects […] to see what they disclose about history, society, nature, or culture'. Bill Brown, 'Thing Theory', *Critical Inquiry*, 28 (1) (Autumn 2001), 1-22 (p. 4). See also *The Object Reader*,

in this thesis is based on an understanding of material culture that sees objects not merely as reflections of historical contexts but as historical actors themselves, that is, as agents alongside humans. As such, artefacts are embedded in social relations, material conditions and culture. And their materiality is part of this. In this thesis, the way a plastic virus model bends, for example, or how the properties of tracing paper affected how one could work with diagrams in science and design practices are shown to be the very stuff of the artefact's position within a range of other aspects of its historical context.

Network models constitute one of the methodologies employed in this thesis that allow for an understanding of objects through processes. Such models, which have their roots in the sociology of science, aid research on cultural transmission because they are based on the idea that institutions and objects are constituted by and embedded in the circulation of ideas, people, practices and things[58]. Design history research employing such models has indicated their suitability to studying subjects that correspond to those investigated in this thesis, such as the movement of material objects or decorative patterns across cultural contexts[59]. As Adamson, Riello and Teasley write, network approaches can illuminate 'how knowledge (of any form, from a decorative pattern or method of weaving to an industrial technique or piece of proprietary software) is transmitted across cultures'[60]. Through investigation of interactions and their conditions, network models complicate narratives of unidirectional 'influence'. For example, Helena Čapková's research on the development of Japanese modernism focuses on networks of Japanese designers who trained in Europe, which, she found, pointed to 'the mutual nature of transnational exchanges rather than […] the one way 'influence' of the Bauhaus and Constructivism on Japan which has been studied in the past'[61].

An understanding of social practices, particularly those concerning the production of crystallographic visualisations, is key to my discussion of the circulation of forms of crystallographic visualisation through networks of figures

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ed. by Fiona Candlin and Raiford Guins (Oxon: Routledge, 2009); *Things That Talk: Object Lessons from Art and Science*, ed. by Lorraine Daston (New York: Zone Books, 2008).

[58] A detailed introduction to 'actor-network theory' is provided in chapter two.

[59] Čapková; Marta Amjar-Wolheim and Luca Molà, 'The Global Renaissance: Cross-cultural Objects in the Early Modern Period', in *Global Design History*, pp. 11-20.

[60] Teasley, Riello and Adamson, 'Introduction: Towards Global Design History', p. 4.

[61] Čapková, p. 370.

active in different fields. This approach to the subject matter through investigations of historically contingent practices constitutes another area of overlap between history of science and design approaches[62].

The biographical approach to studying objects constitutes another key methodology for understanding artefacts in this thesis. It is central to the second half of the thesis, which comprises a biography of ball-and-rod furnishings. This approach involves examining an object, or type of object, as it moves between cultural, historical, geographical, economic or class contexts, across which an object's status, value or meaning might shift. Anthropologists Arjun Appadurai and Igor Kopytoff originally articulated the biographical framework for studying material culture, positing that commodities have 'social lives' conditioned by processes of exchange[63]. This approach has since been used in both histories of design and science to explore the shifting status or significance of objects over time and across contexts[64].

Biographical models are suited to research on cultural transmissions due to their emphasis on movement and shifts in status. This has been realised in the context of global exchange. In *Hokusai's Great Wave: Biography of a Global Icon*, design historian Christine Guth takes a biographical approach to studying the myriad reproductions and 'reconfigurations' of the iconic image of Hokusai's 'Under the Wave off Kanagawa' (often simply called 'The Great Wave') across various cultural contexts[65]. She demonstrates the power of the biographical framework to generate understandings of cultural transmissions in a global context, as an alternative to 'influence' models and associated problematic attributions of agency[66]. Her account locates agency instead in 'spatial flows, and the specificities of geography in this process'[67]. The biography of objects in this

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[62] Literature from science scholarship on practice, configured as such, is noted earlier. This angle is less frequently articulated explicitly in the history of design. A distinct focus on design as a historically or socially-situated practice is found in several texts including Buckley; Attfield, *Bringing Modernity Home*.

[63] *The Social Life of Things: Commodities in Cultural Perspective*, ed. by Arjun Appadurai (Cambridge: Cambridge University Press, 1986); Igor Kopytoff, 'The Cultural Biography of Things: Commoditization as Process', in *The Social Life of Things*, pp. 64-91.

[64] Further discussion of the history of design and history of science literature employing biographical approaches takes place in part two.

[65] Guth, p. 1.

[66] D.J. Huppatz, writing in *Journal of Design History* in 2015 also makes the case for the suitability of biographies of objects as a method for global design history. Huppatz, 'Globalizing Design History'.

[67] Guth, p. 10.

thesis involves different parameters but similarly reframes narratives of cultural transmission previously shaped by an implicit model of 'influence'.

The above approaches to cultural transmission, objects and practices condition the primary sources used in this research. The particular sources relevant to each case, which are outlined in their respective chapters, include the artefacts at the centre of each case study (scientific models and diagrams, artefacts of the FPG, and ball-and-rod objects), accessed through a range of archives. Sources concerning their production, use, circulation, mediation and consumption are also central, and include period print, film, photographic — and where the present is concerned — online sources, and archives of specific scientists, laboratories, manufacturers, retailers and exhibitions[68]. Oral interviewing methods contribute to my accounts of parts of this history that are under-represented in existing primary sources[69].

This thesis is conceived as practice-based history, meant in the sense of 'practice-based research' conventionally used today in art and design colleges. The term describes design and art research that explores methods, materials or the possibilities of a given medium or discipline through practice[70]. History is of course a practice as well, and new insights about conducting this practice can be gained through doing it. A key aspect of this investigation of history as a practice concerns experimentation with methods for interdisciplinary research. Throughout the text I reflect self-consciously on the methodologies used and on issues related to history-writing encountered in the topic area of this thesis. These issues come in for further discussion in the conclusion. But I will briefly note some points associated with interdisciplinary working that impact the text that follows.

Producing an interdisciplinary thesis that attempts to speak to and write from two disciplines brings challenges. Although the case studies are seemingly disparate, each chapter develops insights that contribute to both design history

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[68] Sources and archives consulted are listed in the bibliography.
[69] Detailed information on oral interviews undertaken for this research is provided in the Appendices.
[70] On art and design research 'through' practice see Christopher Frayling's foundational text on the issue, 'Research in Art and Design', *Royal College of Art Research Papers*, 1 (1) (1993/4), 1-5 (p. 5).

and the history of science. On a moment-to-moment (or paragraph-to-paragraph) level, however, I encountered trickier questions about the interdisciplinary arrangement of this work. Should I, for instance, give the science and design contexts 'equal time' in the text on a given subject? This was a concern while writing this introduction, as you may have noticed when I justified the discrepancy in the length of introductions to design and science topics. My response in such situations has been pragmatic. I highlight questions, discourses and subject matter aligned with either the history of design or science as dictated by its relevance and productivity for a given case. A consequence of this aspect of the project's interdisciplinary nature is that there are inevitably stretches of text that might sit more comfortably in one or the other discipline: a description of virus crystallography research carried out in the 1950s, for example, or analyses of postwar CoID interests. But these are, firstly, always in service of larger explorations that generate insights for both disciplines, which I have aimed to signpost clearly in the individual chapters. Secondly, when referencing discipline-specific concepts, topics or discourses, I endeavoured to do so in language that is open to readers from both disciplines.

Historical and geographic parameters

The majority of this research focuses on the 'postwar period', defined here as the period from the end of the Second World War to the early 1960s. It has a second focus on the present, because the questions about cultural transmission posed in this thesis have a deep resonance in the continued lives today of several objects studied here.

The geographical focus of this thesis is broadly described throughout as 'Britain', meaning the United Kingdom, because many of the overarching conditions that frame the study applied nationally: postwar policies affecting industrial design for instance, or today's networks for the exchange of 'retro' commodities. The specific geographic focus of the research, however, centres on London and Cambridge. The actors involved in discussions of science and design are largely tethered to London- and Cambridge-centred networks. These cities were centres of British X-ray crystallographic research in the period covered.

London was also the geographical base for many of the people involved in design policy and practices involved here, and the site of key points of mediation covered, such as the South Bank exhibition of the 1951 Festival. But not all. And in this sense the view provided by this thesis is not comprehensive regarding the consumption, mediation and, to an extent, production of the artefacts studied[71]. This has been conditioned by the sources consulted, the majority of which are held in archives in the southeast of the country. In particular, oral interviews with consumers of designed objects betray a London-focus conditioned by my own residence in London during the period of this research.

Structure

The thesis examines four cases across four chapters. It is split into two halves:

Part one, 'Visualisations in Motion', explores X-ray crystallography visualisations through processes of their construction and use, and in the case of the FPG story, their circulation beyond the scientific community.

Chapter one explores postwar X-ray crystallographers' practices of visualising molecular structures using models and diagrams. A case of modelling associated with virus structure research in the 1950s and early 1960s serves as a lens for studying the role of materials used in constructing models and diagrams in postwar X-ray crystallography practices more widely. The purpose of beginning the thesis in the scientific context is to develop an idea about crystallographic visualisation important to questions of transmission later on: that is, that postwar crystallographic diagrams and models are contingent upon features of postwar scientific practices and training, and open to material and formal adaption throughout the process of making. These points are linked to this chapter's description of the production of visualisations as a craft practice. Virus research by X-ray crystallographers in this period also evidences the currency in the field of specific ideas about natural morphologies that also circulated among some postwar British design networks, leading to and emerging from interdisciplinary dialogue.

[71] See Buckley regarding the fact that much twentieth-century British design history is uncritically London-centred. This issue is discussed further in the thesis conclusion.

Chapter two is a history of the FPG from the perspective of the translation and transmission of crystallographic diagrams from science to industrial design. It builds on chapter one's ideas of contingency, craft, and materiality in crystallographic visualisation practice, and expands on the topic of the shared ideas, dialogue and personal networks linking X-ray crystallographers and actors in design circles. This chapter focuses on crystallographer Helen Megaw's practice of producing diagrams for use by the FPG, and the shifting meaning of her diagrams as they circulated among networks of designers, artists and the custodians of British design policy in the CoID. This yields insights on the aesthetic frameworks operating in postwar modernist networks that conditioned this experiment in science-inflected pattern design. It also reflects on the circulation of X-ray crystallography knowledge (in the form of its diagrams) among figures in fields outside of scientific research.

Part two, 'A Biography of Postwar British Ball-And-Rod Furnishings', explores ball-and-rod objects across the era of their production and today.

Chapter three presents the postwar history of ball-and-rod objects, which have previously not been subject to such empirical research. It surveys the production, mediation and consumption of these furnishings in the period. A central component of this chapter is the investigation of the question of their reference to crystallographic visualisation, continuing an exploration launched in chapter two into the role of scientific ornament in postwar British modernist design. This involves exploring the relationship between ball-and-rod objects and the mediation of crystallographic forms in postwar British popular culture by way of BBC science television and postwar exhibitions. Consequently, although framed as a design history of postwar British ball-and-rod furnishings, this chapter challenges the discipline's conventions through its interdisciplinary scope, which includes an investigation of science in culture.

Chapter four continues the biography of ball-and-rod objects in their contemporary lives and consumption as 'retro' commodities. It explores the display of postwar ball-and-rod objects on the online auction site ebay.co.uk and their significance in the lives and homes of contemporary consumers, arguing that associations with postwar science emerge most strongly through the consumption and use of these objects today. This chapter examines the ways in which these objects operate as mediators of historical narratives in 'retro' culture. It poses questions about the relationship between popular memory and professional history practice, and the ways in which contemporary categories inflect the historiography on the subjects explored in this thesis.

This chapter sequence does not imply a linear narrative of transmission from X-ray crystallography research to the FPG to ball-and-rod furnishings. In fact this research challenges models of such a one-way, linear trajectory. Instead the thesis unfolds thematically and through the development of findings that build upon one another.

Contributions

This thesis is about and performs border-crossings: between X-ray crystallography and industrial design in the past; between current academic disciplines; and between the past and present lives and narratives of objects, which are created across different genres of history-writing. Its contributions are therefore of three orders:

Historical: This thesis contributes original insights to both history of science and history of design discourses. It develops a detailed understanding of social networks and flows of ideas, images and objects that did – and did not – contribute to mechanisms of exchange between fields of postwar British industrial design and X-ray crystallography. This understanding revises existing historiography on such cross-field transmissions in postwar Britain. It also contributes to the history of postwar British science through research on X-ray crystallography practice and the reception of the science in cultures outside of it. This research also contributes to the history of postwar British modernist design from the under-explored perspective of science-inflected ornament.

Methodological: This thesis articulates the study of relationships between science and design in the past as a distinct interdisciplinary research area. It proposes methods for research in this territory through experiments in interdisciplinary approaches. These methods forge new relationships between the histories of science and design, and reframe their conventions and questions. The methodological inquiries of this thesis show that these disciplines have in many ways housed parallel inquiries in recent decades, and can benefit from greater exchange between them, which has so far been rare.

Historiographical: In the process of developing new narratives of cultural transmission between science and design in postwar Britain, this thesis reflects on the categories, assumptions, disciplinary perspectives and contemporary cultural factors that shape the existing historiography. In doing so, this text also reflects on history-writing itself.

Part One: Visualisations in Motion

Chapter One

Plastic, Plasticine and Tracing Paper: The Craft of Postwar X-ray Crystallographic Visualisation

Introduction

Commentators on postwar X-ray crystallography have compared this science to craft in a casual, surface manner. In her historical account of women in the field, X-ray crystallographer Maureen Julian wrote that 'intellectual knitting' was a common epithet for crystallography among scientists in other disciplines[1]. This both characterises X-ray crystallography as a form of technical or physical handcraft and references (perhaps misogynistically) an activity traditionally associated with female labour, thus serving as shorthand for the role of women in the field[2]. Its derisive overtones aside, 'intellectual knitting' is typical of evocations of 'craft' in this context; they often reference the technical aspects of crystallographic practice, which included taking X-ray photographs and building models[3]. A Royal Society portrait of the Oxford X-ray crystallographer Dorothy Hodgkin by the artist Henry Moore signals handcraft as well: the drawing pictures only Hodgkin's hands, which were afflicted for most of her life by arthritis, thus accentuating the direct implications of Hodgkin's illness for her work in a science that was dependent upon handwork (Figure 1).

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[1] Maureen M. Julian, 'Women in Crystallography', in *Women of Science: Righting the Record*, ed. by G. Kass-Simon and Patricia Farnes (Bloomington: Indiana University Press, 1990), pp. 335-383 (p. 335).

[2] Early to mid-twentieth-century crystallography is known for its relative openness to women compared to other physical sciences at the time. Female crystallographers in this period achieved significant and high profile milestones: in 1964 Dorothy Hodgkin won a Nobel Prize in chemistry, Kathleen Lonsdale was one of the first women elected to the Royal Society in 1945, and Rosalind Franklin contributed crucially to the elucidation of the DNA double helix in 1953. The number of women in crystallography was not high in absolute terms however. Julian points out that women accounted for just 3% of crystallographers by 1962. Julian; Georgina Ferry, 'Women in Crystallography', *Nature*, 505 (30 January 2014), 609-611; Sharon Bertsch McGrayne, *Nobel Prize Women in Science: Their Lives, Struggles, and Momentous Discoveries* (New York: Birch Lane Press, 1993).

[3] For example, a recent Royal Society lecture by X-ray crystallographer Dorothy Hodgkin's biographer Georgina Ferry, entitled 'Women's Work: Dorothy Hodgkin and the Culture and Craft of X-ray Crystallography', reflected on the social issues facing a female scientist in mid-twentieth century Britain, and used the word 'craft' to signify X-ray crystallography techniques and Hodgkin's technical skill. Georgina Ferry, 'Women's Work: Dorothy Hodgkin and the Culture and Craft of X-ray Crystallography', Lecture at the Royal Society, London. 4 April 2014.

Figure 1 Henry Moore, *Dorothy Hodgkin's Hands* (1978).

Yet despite nods in its direction, the relationship between X-ray crystallography and craft has not been interrogated. This chapter explores what happens when we examine it seriously, taking on perspectives from the history and theory of craft. Specifically, this chapter conceives of practices of X-ray crystallographic visualisation as a form of craft. I will investigate scientists' processes of making and working with models and diagrams in postwar X-ray crystallography research. This investigation is framed by a case study of postwar virus modelling, which I examine through the lens of craft scholarship from design history discourse – a lens that is rarely brought to bear on scientific topics. This chapter's resulting examination of crystallographic visualisation both generates insights on the history of postwar X-ray crystallography and opens up the subject of crystallographic visualisation to study from history of design perspectives. In doing so, it also prepares the ground for discussions of the transmission of crystallographic visualisations to design later in the thesis.

Three principle aims frame this chapter. Firstly, it advances a methodological tool for studying crystallographic visualisation. This chapter demonstrates the utility for history of science research of incorporating approaches from design and craft scholarship into studies of scientific visualisation practices. This cross-disciplinary methodology, in turn, also challenges the conventional boundaries of design history research, for it establishes scientific models and diagrams as subject matter for design scholarship. The methodological experiment of this chapter contributes to one of the overall aims of this thesis: to reframe the conventional boundaries of design history and the history of science in ways that will allow for the productive examination of objects that straddle, migrate between, or challenge these boundaries. This chapter investigates rarely acknowledged shared concerns operating in history of science and design history scholarship and the consequent potential for cross-fertilisation between the two.

Secondly, this chapter's investigation of X-ray crystallographic visualisation as a craft process contributes to the history of X-ray crystallography specifically. It explores new empirical examples of the role of materiality in postwar practices of crystallographic visualisation[4]. For science scholars, artefacts such as physical models and diagrams raise questions about their role (and that of materiality) in knowledge generation in scientific practice, and the social factors conditioning their use[5]. This chapter investigates specific historical contingencies, including the training of postwar crystallographers, that shaped the form and use of models and diagrams in postwar British crystallography research. In this investigation, approaches from craft scholarship allow for a deeper understanding of the materiality of postwar crystallographic visualisation practices than has been previously pursued in the historiography on crystallography. This chapter also yields insights on further aspects of the postwar culture of British X-ray crystallography and on its exchange with other fields (discussed below).

Third, although this chapter is more heavily focused on a scientific topic than the other chapters in this thesis, it nevertheless contributes to the study of cultural transmission between crystallography and design in this thesis. In addition to providing necessary background information on postwar X-ray crystallography, it also generates a historically contingent understanding of

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[4] This chapter focuses on crystallographers' production of visualisations in research contexts as opposed to visualisations produced specifically for communication among scientists, teaching or public display. Models used for display frequently differed in their production methods and materiality from the models used for research purposes. There was however at times a fine line between the research and display model (as de Chadarevian indicates, for instance, sometimes a completed research model subsequently became useful as a demonstration model). de Chadarevian, 'Models and the Making of Molecular Biology'.

[5] This literature is surveyed below in the section entitled 'A material approach to studying visualisation practice'.

crystallographic visualisation that is necessary to discussions of transmissions between science and design later on. In this sense, it contrasts with much science scholarship on representations, for my conclusions will point back not only to the scientific context, but will also contribute to analyses of subject matter conventionally studied by design historians. I argue throughout this thesis that to understand the history of cross-disciplinary relationships, it is important to understand both fields not as monolithic entities (as 'science' often appears in design histories) but as constituted by material contingencies, and social practices and interactions. This is one reason why this chapter's exploration of the contingent nature of postwar crystallographic visualisation is important (and why I emphasise this point, which may appear quite obvious to a historian of science). I contend that such understandings of the social and material dimensions of scientific practice will enrich further study of science-inflected design, which, as I noted in the introduction, currently engage with science only fleetingly.

This chapter's exploration of postwar crystallographic visualisation is framed by a case study of modelling in the virus research of the South African-born British biophysicist Aaron Klug and his US collaborator Don Caspar. They employed X-ray crystallography and electron microscopy data-gathering techniques to study virus structures in the 1950s and early 1960s. During this time Klug was a member of Birkbeck College's Crystallography Department in London and, from 1962, of the Laboratory of Molecular Biology (LMB) in Cambridge.

My investigation of this case employs a seemingly unlikely source: a television programme. The first episode of the BBC science programme *Horizon*, 1964's 'The World of Buckminster Fuller', explored the idiosyncratic inventor/designer's career through the lens of his interest in natural forms and structures[6]. The episode is partly devoted to an exchange that had taken place approximately four years earlier between Fuller and Klug. This exchange concerned similarities in the structures of some viruses to Fuller's geodesic domes (Figure 2), and it affected Klug and Caspar's research (as I will explain

[6] 'The World of Buckminster Fuller', *Horizon*, BBC2, 2 May 1964.

later in the chapter). The programme is a unique and productive historical source for the purposes of this research because it offers a glimpse of something that is rather ephemeral, but which has great bearing on questions about scientific objects: that is, the physical interaction between scientist and model in the past. This episode of *Horizon* included a conversation between Klug and Fuller, filmed as they stood before a menagerie of Klug's three-dimensional virus models. The models were made of a variety of materials and components including a construction toy, Geodestix, which Caspar and Klug had adapted for use in virus modelling from Fuller's practice. Together Klug and Fuller manipulate models on-air, reflecting on the material properties of these objects and the ways in which virus modelling acted as a site for exchange of knowledge between them[7]. Their conversation constitutes a key source in my analysis later in the chapter.

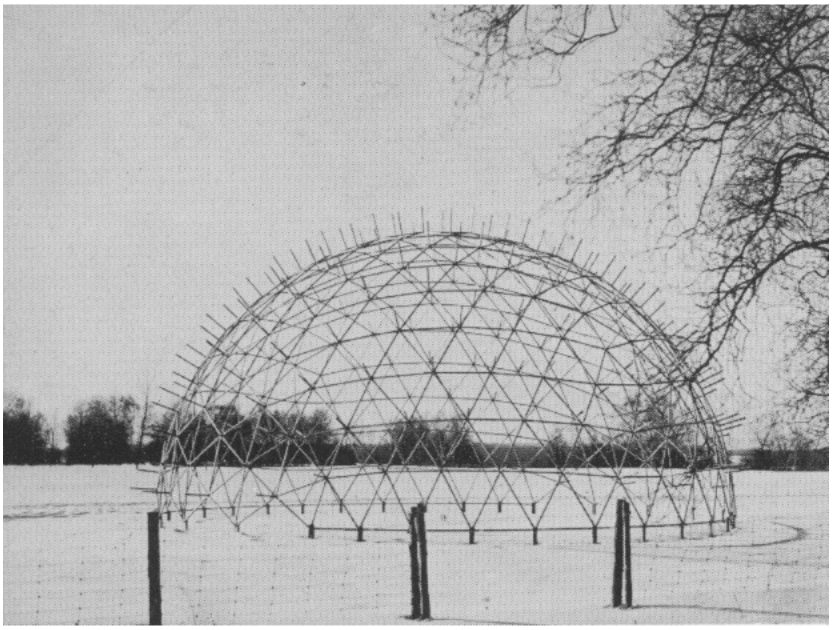

Figure 2 A geodesic dome designed by Buckminster Fuller, erected in Montreal in December 1950.

The primary case explored in this chapter centres on Klug and Caspar's use of Geodestix as components for virus models (Figures 3 and 4). At first glance this might appear to be an unusual case through which to study postwar

[7] Unfortunately the BBC has no available still images of this episode of *Horizon* so throughout this chapter the interactions on this programme of relevance to my study will be represented verbally, without the aid of illustrative images.

British crystallographic visualisation: virus models are perhaps not the first objects to spring to mind when it comes to crystallography models (postwar X-ray crystallography is more commonly associated with ball-and-spoke molecular models); objects associated with Buckminster Fuller are involved, which was unusual (indeed this is partly why the case received television coverage); it is not limited exclusively to British X-ray crystallographers given Klug's transatlantic collaboration with Caspar; and their virus modelling was not based exclusively on X-ray crystallographic data. In these seeming aberrations, however, this case is in fact revealing of many key aspects of the postwar culture of X-ray crystallography in Britain. As I show in this chapter, postwar crystallographic visualisation was defined by the variety and mutability of visual and material forms used and by the varied backgrounds of crystallographers. Entering the subject from this seemingly odd angle offers us a picture of postwar X-ray crystallographic practice and its associated objects correspondent with the internal variety that characterised the field.

As noted above, this chapter does not focus on transmissions between design and crystallography as explicitly as those that follow it, because the focus is X-ray crystallographic practice. The cross-field dialogue between Fuller and Klug, involved in the case studied, is in many ways not generalisable: it is not a springboard for observations about communication between postwar X-ray crystallographers and designers or architects. Nor do I make a claim that this exchange had a causal relationship to any subsequent interactions between scientists and actors in other fields. But Fuller and Klug's exchange is relevant to my broader examination of cultural transmission between X-ray crystallography and industrial design for two reasons. Firstly, the case study explored here demonstrates crystallographic visualisation as a potential site for cross-disciplinary exchange, a point developed further in chapter two. Secondly, Fuller and Klug's encounter is a product of what I will show in the next chapter was a significant channel for communication between actors in X-ray crystallography and industrial design. Their meeting emerged out of the operation of specific cross-field networks linking postwar X-ray crystallographers and practitioners in design and art fields. Therefore, in addition to reflecting on the field of X-ray crystallography itself, this case also contributes to a greater understanding of links between X-ray crystallography and other fields, providing further foundation for discussions of cultural transmission later in the thesis.

Following an introduction to my approach and sources, this chapter provides background on X-ray crystallography techniques, visualisation conventions, and the major research strands and centres of X-ray crystallography in Britain by the mid-twentieth century. I will then analyse the case study of Klug and Caspar's use of Geodestix as a modelling tool in their virus research. This subsequently frames a broader discussion of postwar crystallographic visualisation as a craft process, and the insights gained from this research regarding the culture of postwar British X-ray crystallography.

Figure 3 Selection of Aaron Klug's virus models in the archive of Cambridge's Laboratory of Molecular Biology (LMB). These include virus models made of rubber tubing, ping-pong balls, paper and Geodestix. A small yellow and red Geodestix model is visible on the right on the top shelf.

Figure 4 Virus models made from Geodestix at the LMB's Archive.

A material approach to studying visualisation practice

Since the late 1970s, scholars focusing on science as a practice have looked to the active role therein of what they variously term visualisations, representations, inscriptions, 'paper tools' and 'nomenclature'[8]. In *Laboratory Life*, a now-canonical text on the subject, sociologists of science Bruno Latour and Steve Woolgar described scientific practice as a 'series of transformations' leading to, essentially, marks on paper. A process might begin with a sample taken from a rat, for instance, and 'the end product is no more than a curve, a diagram, or a table of figures written on a frail sheet of paper', they write[9]. The idea being that such 'inscriptions' are not supplementary to the primary work of scientific research; the work leading to them, and work with inscriptions, constitutes scientific practice itself. Therefore, understanding the nature of such practices of representation aids understanding of knowledge generation and communication in the sciences and the contingencies shaping it.

In the last decade, the recent 'object turn' in the humanities and growing interest in the material culture of science have seen science historians push beyond this focus on the two-dimensional, staking out a place for three-dimensional models acting alongside people as integral research and communication tools[10]. Traditionally the term 'model' in studies of history and

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[8] This was initiated primarily by authors in science and technology studies, and subsequently taken up by historians of science. *Visualisation in the Age of Computerization*, ed. by Annamaria Carusi, Aud Sissel Hoel, Timothy Webmoor and Steve Woolgar (New York: Routledge, 2015); *Representation in Scientific Practice Revisited*, ed. by Catelijne Coopmans, Janet Vertesi, Michael Lynch, and Steve Woolgar (Cambridge, Massachusetts: MIT Press, 2014); Jenny Bangham, 'Writing, Printing, Speaking: Rhesus Blood-Group Genetics and Nomenclatures in the Mid-Twentieth Century', *The British Journal for the History of Science*, 47 (2) (2014), 335-361; Lorraine Daston and Peter Galison, *Objectivity* (New York: Zone Books, 2010); David Kaiser, *Drawing Theories Apart: The Dispersion of Feynman Diagrams in Postwar Physics* (Chicago: University of Chicago Press, 2005); Ursula Klein, *Experiments, Models, Paper Tools: Cultures of Organic Chemistry in the Nineteenth Century* (Stanford, CA: Stanford University Press, 2003); *Tools and Modes of Representation in the Laboratory Sciences*, ed. by Ursula Klein (Dordrecht: Kluwer Academic, 2001); Ursula Klein, 'Paper Tools in Experimental Cultures', *Studies in History and Philosophy of Science*, 32 (2) (2001), 265–302; *Representation in Scientific Practice*, ed. by Michael Lynch and Steve Woolgar (Cambridge, Massachusetts: The MIT Press, 1990); Latour and Woolgar; Michael Lynch, 'The Externalized Retina: Selection and Mathematization in the Visual Documentation of Objects in the Life Sciences', *Human Studies*, 11 (2/3) (1988), 201-234.

[9] Latour and Woolgar, p. 50.

[10] Lorraine Daston, 'The Glass Flowers', in *Things That Talk*, pp. 223-254; *Models: The Third Dimension of Science*; Eric Francoeur, 'Molecular Models and the Articulation of Structural

philosophy of science had signified only concepts[11]. Recent scholarship exploring three-dimensional models includes de Chadarevian's research on postwar protein X-ray crystallography within her research on the postwar rise of molecular biology in Cambridge, upon which this examination builds. She identifies protein crystallography models as historical actors, circulating alongside tools and researchers in the development of the science[12]. She emphasises the importance of models, as physical objects, in research and communication processes, notes crystallographers' 'inventive' modelling processes and use of varied materials, and describes the constitution of some models, but in-depth analysis of materiality or its role in the research process is not her focus[13].

My consideration of crystallographic visualisations (including models and diagrams) is in sympathy with recent calls within the history and philosophy of science (HPS) to examine models as physical objects 'in making and use'[14]. Scholars acknowledge that examining scientific representations from the perspective of their materiality aids understandings of the ways in which they mediate interactions (among scientists and between scientists and other audiences, for example), and that the epistemic function of models in research is tied to their physical attributes and use[15]. Philosopher of science Tarja Knuuttila writes that a model's 'cognitive value is largely based on manipulation'[16]. She

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Constraints in Chemistry', in *Tools and Modes of Representation in the Laboratory Sciences*, ed. by Ursula Klein (Dordrecht: Kluwer Academic, 2001), pp. 95-115; Eric Francoeur, 'Beyond Dematerialization and Inscription: Does the Materiality of Molecular Models Really Matter?', *HYLE – International Journal for Philosophy of Chemistry*, Vol. 6 (2000), 63-84; Eric Francoeur, 'The Forgotten Tool: The Design and Use of Molecular Models', *Social Studies of Science*, 27 (1) (February 1997), 7-40.

[11] Key texts on theoretical models include Mary B. Hesse, *Models and Analogies in Science* (London: Sheed and Ward, 1963); Nancy Cartwright, *How the Laws of Physics Lie* (Oxford: Oxford University Press, 1983); Mary S. Morgan and Margaret Morrison, *Models as Mediators: Perspectives on Natural and Social Science* (Cambridge: Cambridge University Press, 1999).

[12] de Chadarevian, 'Models and the Making of Molecular Biology'; de Chadarevian, *Designs For Life*;

[13] de Chadarevian, 'Models and the Making of Molecular Biology', p. 344; de Chadarevian, *Designs for Life*.

[14] Tarja Knuuttila, 'Modelling and Representing: An Artefactual Approach to Model-Based Representation', *Studies in History and Philosophy of Science*, 42 (2011), 262-271; James Griesemer, 'Three-Dimensional Models in Philosophical Perspective', in *Models: The Third Dimension of Science*, pp. 433-442 (p. 437); Nick Hopwood and Soraya de Chadarevian, 'Dimensions of Modelling', in *Models: The Third Dimension of Science*, pp. 1-15.

[15] See *Models: The Third Dimension of Science* and *Representation in Scientific Practice Revisited*.

[16] Knuuttila, p. 268.

suggests therefore that models be considered as ‘concrete’, and ‘unfolding’[17]. Some recent HPS research takes this on, approaching the physical properties of models and users’ interactions with them, but evidence-based historical examples are scarce[18]. Most existing analyses of twentieth-century practices stop short of in-depth explorations of materiality, that is, of investigating the role of specific materials in scientific practice and the interactions and opportunities they afford users.

Materiality is a richer subject for some historians of early modern science today. It arises in discussions of the role of artisans and associated modes of craftsmanship in histories of science during this period when in many cases the practices and knowledge of artisans and those who we might now call ‘scientists’ came into contact[19]. Such research builds on historian Edgar Zilsel’s claim that the scientific revolution depended on intellectuals’ social acceptance of practical artisan knowledge[20]. For instance, historian Pamela Smith reads early modern metalworkers’ use of butter and mercury as part of what she terms the ‘vernacular science of matter’, or ‘how making with natural materials was also about knowing nature in a generalized sense’[21]. This literature focuses heavily on interactions between practitioners from different fields and associated complex encounters of different kinds of knowledge: ‘learned’ or ‘theoretical’ knowledge of intellectuals practicing science on one hand and the ‘practical’, ‘empirical’ or ‘craft knowledge’ of artisans and engineers on the other[22]. Although conditions of early modern and mid-twentieth century science differ, the attention to the

[17] Ibid, p. 263.
[18] Eric Francoeur has broached the topic of the materiality of forms of chemistry modelling, arguing that ‘what can be understood in the broadest sense as the materiality of the signs used by chemists in the course of their work does somehow, in some circumstances, matter’. Francoeur, ‘Beyond Dematerialization and Inscription’, p. 65; Francoeur, ‘Molecular Models and the Articulation of Structural Constraints in Chemistry’; Francoeur, ‘The Forgotten Tool’.
[19] *Ways of Making and Knowing: The Material Culture of Empirical Knowledge*, ed. by Pamela H. Smith, Amy R.W. Meyers, and Harold J. Cook (Ann Arbor: The University of Michigan Press, 2014); Domenico Bertoloni Meli, *Thinking with Objects: The Transformation of Mechanics in the Seventeenth Century* (Baltimore, 2006); Pamela H. Smith, *The Body of the Artisan: Art and Experience in the Scientific Revolution* (Chicago: University of Chicago Press, 2004); Long, *Openness, Secrecy, Authorship: Technical Arts and the Culture of Knowledge from Antiquity to the Renaissance* (Baltimore: 2001).
[20] Edgar Zilsel, *The Social Origins of Modern Science* (Dordrecht: Kluwer Academic, 2000).
[21] Pamela H. Smith, ‘Making as Knowing: Craft as Natural Philosophy’, in *Ways of Making and Knowing*, pp. 17-47 (p. 18).
[22] Long, *Artisan Practitioners and the Rise of the New Sciences*, p. 8; Smith, *The Body of the Artisan*, p. 6; Smith, ‘Making as Knowing’.

materiality and social conditions of different kinds of knowledge in scientific practice in this literature provides a model for my analysis.

In order to explore crystallographic visualisations from a perspective of their materiality, this examination draws on approaches from design and craft scholarship. The word 'craft' has numerous uses. It conventionally describes a category of applied arts including ceramics, woodworking, etc. (many of which, historian Paul Greenhalgh points out, are grouped together somewhat arbitrarily 'only by virtue of their exclusion' from the category of fine art)[23]. In science scholarship, descriptions of science as 'craft' or 'craftwork' highlight laboratory skills and routines as central to scientific knowledge production[24]. Much of this builds on philosopher Michael Polanyi's 1958 contention that 'tacit knowledge' (or knowledge that cannot be articulated easily in words) operates in scientific practice[25]. In this literature 'craft' rarely accompanies detailed material analysis or perspectives from craft scholarship, as it is a descriptor for tacit knowledge, and/or laboratory work.

Although this chapter adopts a similar science-as-practice angle to such studies, I write primarily in the spirit of recent scholarship from design history and theory discourse, because, I argue, it allows the researcher to take on calls within HPS to explore the materiality of scientific practices of representation more deeply[26]. In particular I draw upon recent conceptions of craft as a broad

[23] Paul Greenhalgh, 'The History of Craft', in *The Culture of Craft*, ed. by Peter Dormer (Manchester: Manchester University Press, 1997), pp. 20-52 (p. 28).
[24] Key texts in this area include Kaiser; Shapin and Schaffer; Joan H. Fujimura, *Crafting Science: A Sociohistory of the Quest for the Genetics of Cancer* (Cambridge, Massachusetts: Harvard University, 1996); Latour and Woolgar; Jerome R. Ravetz, *Scientific Knowledge and Its Social Problems* (New Brunswick, New Jersey: Transaction, 1996 [1971]); Michael Polanyi, *Personal Knowledge: Toward a Post-Critical Philosophy* (Chicago, University of Chicago Press, 1958).
[25] Polanyi, *Personal Knowledge*, p. 96; Michael Polanyi, *The Tacit Dimension* (Chicago, University of Chicago Press, 1966).
[26] Recent decades have seen a growing body of literature on craft aligned with design history and theory discourse. Much of this literature aims to rehabilitate the status of craft in relation to fine art (which traditionally overshadows craft in hierarchies of the arts) as a practice and subject of scholarship. Key texts include Glenn Adamson, *The Invention of Craft* (London: Bloomsbury, 2013); *The Power of Making*, ed. by Daniel Charny (London: V&A, 2011); *The Craft Reader*, ed. by Glenn Adamson (Oxford: Berg, 2010); Glenn Adamson, *Thinking Through Craft* (Oxford, Berg, 2007); Howard Risatti, *A Theory of Craft: Function and Aesthetic Expression* (Chapel Hill: University of North Carolina, 2007); Paul Greenhalgh, *The Persistence of Craft: The Applied Arts Today* (London: A&C Black, 2002); *The Culture of Craft*; Peter Dormer, *The Art of the Maker* (London: Thames and Hudson, 1994). See also Richard Sennett, *The Craftsman* (London: Allen Lane, 2008).

category of production processes united by their lack of complete automation[27]. Design historian Glenn Adamson's work is integral to this conception of craft. Craft, he writes, is 'the application of skill and material-based knowledge to relatively small-scale production'[28]. Crucial to this chapter is the idea, also voiced by Adamson, of craft as a process, in which '*material* experience' is central[29]. Rather than a 'fixed set of things', he writes, craft is

> an approach, an attitude, or a habit of action. Craft only exists in motion. It is a way of doing things, not a classification of objects, institutions, or people[30].

Thinking through the lens of craft in this chapter opens up investigation of processes of making visualisations, of their materiality and associated interactions between scientists, their materials, and other actors embedded in different practices. This lens thus provides methodological tools for pursuing more in-depth understanding of scientific representations as relational, material objects in scientific practice; craft scholarship is attuned to the 'concrete', and 'unfolding' nature of objects that scholars of scientific objects now aim to investigate[31].

Sources

If, as Adamson puts it, craft 'only exists in motion', challenges arise when it comes to truly studying such processes that were performed in the past[32]. In the case of postwar crystallographic visualisation, little documentation of practices

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[27] An indication of the recent consolidation of a field of craft scholarship under this broader conception of craft was the establishment of an academic journal the *Journal of Modern Craft* in 2008, which 'addresses all forms of making that self-consciously set themselves apart from mass production'. This opens up its interdisciplinary possibilities. An example of a recent cross-disciplinary application of craft scholarship is Tim Dornan and Debra Nestel's exploration of medicine through the lens of craft in which the authors think through the consequences of contemporary developments in medical practice that impose the certainty and 'logic of the modern production line' and limit doctors' dialogic processes of engaging with patients (described as a craft practice). 'Talking, Touching, and Cutting: The Craft of Medicine', *The Journal of Modern Craft*, 6 (1) (March 2013), 35-48 (p. 36); The Journal of Modern Craft, 'About', http://journalofmoderncraft.com/about-2. Accessed 6 June 2015.

[28] Glenn Adamson, 'Introduction', in *The Craft Reader*, pp. 1-5 (p. 2).

[29] Adamson, *Thinking Through Craft*, p. 4.

[30] Ibid, p. 3.

[31] Knuuttila, p. 263.

[32] Adamson, *Thinking Through Craft*, p. 4.

of producing diagrams or models exists. Additionally, crystallographers rarely commented in any detail on their processes of building models or drawing diagrams. This is not uncommon in twentieth century sciences generally[33]. Additionally, because such objects were used in the research process as ephemeral tools, many do not survive (modelling materials were often recycled between projects[34]). Even surviving artefacts provide little insight as to their use and processes of making. One would need to be an observer in the laboratory to apprehend these interactions. Consequently, amidst the calls to consider models as objects, and as 'unfolding'[35], it is actually difficult to demonstrate the material details of their construction and use in the past.

This does not mean, however, that we cannot study crystallographic visualisations. This chapter demonstrates that the photographic and film record provides evidence of use and even, in the case discussed here, interaction. It draws upon early BBC science television, accessed in the British Film Institute National Archive, as a valuable source of researcher-model interactions in motion.

Although this is not a comprehensive study of postwar X-ray crystallographic practice (which would require more space), the specific case studied frames a broader analysis of postwar British crystallographic visualisation practice. This analysis draws upon primary research on the Laboratory of Molecular Biology (LMB) (one of the only centres of British X-ray crystallography with an archive), involving consultation of their collection of models and modelling components, laboratory order books, and an oral interview with the laboratory's technician-turned-manager throughout the postwar decades, Mike Fuller. Additional sources consulted include X-ray crystallography models held in the Science Museum Archives; photographs of models and diagrams published in scientists' papers; crystallographer Helen Megaw's papers held in Cambridge's Girton College Archive; oral interviews with X-ray

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[33] Modelling is among those facets of scientific research that Maura Flannery, writing on the merging of 'the objective and subjective' in biology, comments, 'are not considered under the "Methods" section' of most scientific papers, even though 'they might well be among the most important methods that distinguished researchers use in their work'. Maura C. Flannery, 'Goethe and the Molecular Aesthetic', *Janus Head*, 8 (1) (2005), 273-289 (p. 282).
[34] de Chadarevian, 'Models and the Making of Molecular Biology'.
[35] *Models: The Third Dimension of Science*; Knuuttila, p. 263.

crystallographer Michael Glazer, Emeritus Fellow of Jesus College Oxford; and postwar crystallographers' published accounts and past oral interviews.

1. Mid-twentieth-century X-ray crystallography

Before analysing crystallographic visualisation as craft through the case study of Klug and Caspar's virus modelling, I first introduce the state of mid-century X-ray crystallography in Britain: techniques, basic forms of visualisation used, major research areas and centres. This provides background for the analyses later in this chapter and in chapter two.

The birth of X-ray crystallography

X-ray crystallography was developed in the early 1910s by the father and son William Henry (W.H.) and William Lawrence (W.L.) Bragg, physicists then based at Leeds and Cambridge Universities respectively. They built on research led in 1912 by physicist Max von Laue, who obtained X-ray images indicating that when X-rays passed through a crystal, the atoms inside diffracted them, meaning they spread apart and interfered with each other (Figure 5)[36].

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[36] On the development of X-ray crystallography see Authier; *Historical Atlas of Crystallography*; Olby, *The Path To The Double Helix*; *Fifty Years of X-ray Diffraction*.

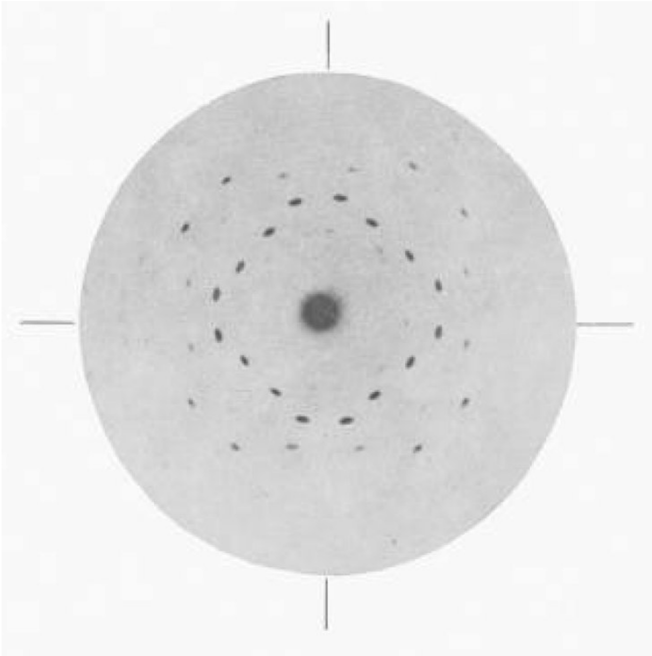

Figure 5 Diffraction photograph of Zincblende published by Max von Laue and his collaborators Walter Friedrich and Paul Knipping in 1912.

There was much to be gained from this experimentation concerning the nature of X-rays (for one thing, it contributed to on-going debate about whether the rays were particles or waves). But the Braggs used this property of crystals (that they can diffract X-rays) for the specific purpose of gleaning information about the placement of atoms in crystals. W.H. Bragg designed instrumentation to carry out these investigations, and W.L. Bragg, then still a student, devised an equation for analysing the diffraction pattern in order to determine positions of atoms relative to one another[37].

Their research transformed the study of crystals, which had existed long before the twentieth century. It had roots in ancient thinking on geometry, mineral classification and morphology, and in early experiments in optics. In the eighteenth century crystallography became a circumscribed field, largely devoted to mineralogical research[38]. Crystallographic study had long provoked

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[37] The younger Bragg first presented this equation, known as Bragg's Law, in 1913 at the age of 22 (W.L. Bragg, 'The Diffraction of Short Electromagnetic Waves by a Crystal', *Proceedings of the Cambridge Philosophical Society*, 17 (1) (10 January 1913), pp. 43-57).

[38] On pre-twentieth-century crystallography see Henk Kubbinga, 'Crystallography from Hauy to Laue: Controversies on the Molecular and Atomistic Nature of Solids', *Foundations of Crystallography A*, 68 (2012), 3-29; John G. Burke, *Origins of the Science of Crystals* (Berkeley: University of California Press, 1966). The early history of crystallography is also touched on in Authier; *Historical Atlas of Crystallography*; Ewald.

speculations upon the structure of matter[39]. But before X-ray diffraction methods, there was no way to look inside a crystal to confirm its internal constitution. In 1915, the Braggs wrote, now, 'Instead of guessing the internal arrangement of the atoms from the outward form assumed by the crystal, we find ourselves able to measure the actual distances from atom to atom'[40]. They won a joint Nobel Prize for the development of X-ray crystallography that year.

British X-ray crystallography: research and centres

Outposts of X-ray crystallography research developed in Britain in the decades following the Braggs' early work in the field. In 1919 W.L. Bragg became chair of physics at Manchester. W.H. Bragg set up a research group at the Royal Institution in 1923. Students from both centres later headed crystallography departments elsewhere. For example, at Cambridge's Cavendish Laboratory of Physics, a Crystallography Laboratory was established in 1931, headed by J.D. Bernal (a student of W.H. Bragg)[41]. In 1948 Bernal became the head of a Crystallography Department established within the Physics Department at London's Birkbeck College[42]. In 1949 Kathleen Lonsdale, also a student of W.H.

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[39] The study of crystals aided speculations on the structure of matter particularly through the seventeenth and eighteenth centuries, such as the seventeenth-century natural philosopher Robert Boyle's theory that matter was composed of minute particles that gather into 'corpuscles'. In the late eighteenth- and early nineteenth-centuries, René Just Haüy, often credited as the 'father of crystallography', proposed that crystals comprise stacks of identical subunits ('*molécules intégrantes*'), which determine the externally measurable geometry of a crystal. Haüy's theory speaks to the notion of a crystal's repeating unit cell, the smallest unit of its repeating structure, later confirmed by X-ray diffraction. By the early twentieth century crystallographers had developed methods inferring information about the internal structures of crystals through studies of external form and mathematical reasoning. This was aided by the enumeration of 32 possible symmetry classes that might describe a given crystal structure, which are divided into seven crystal systems defining the axes along which a given crystal's symmetry might be articulated (cubic or tetragonal symmetry, for example). Burke, p. 30; Authier, p. 326; *Fifty Years of X-ray Diffraction*.

[40] William Henry Bragg and William Lawrence Bragg, *X-rays and Crystal Structure* (London: G. Bell and Sons, 1915), p. 4.

[41] The crystallography group was transferred from the Mineralogy Department at Cambridge to the Cavendish in 1931, probably in response to the increasingly broad class of subject matter explored within crystallography beyond mineral structures since the advent of X-ray crystallography. John Finch, *A Nobel Fellow on Every Floor: A History of the Medical Research Council Laboratory of Molecular Biology* (Cambridge: The Medical Research Council Laboratory of Molecular Biology, 2008).

[42] *J.D. Bernal: A Life in Science and Politics*; J.D. Bernal, 'Crystallography in Britain During and After World War II', in *Fifty Years of X-ray Diffraction*, pp. 384-397.

Bragg, became the head of a Department of Crystallography at UCL[43]. Industrial laboratories, such as the General Electric Company (GEC) and Imperial Chemical Industries (ICI), also took up X-ray crystallography research[44].

Throughout the field's twentieth-century expansion, X-ray crystallographers came from several disciplinary backgrounds and worked across disciplinary contexts. Consequently crystallographers in the period often require two-fold designations: in addition to 'crystallographer' one might have identified also as a biochemist or physicist for example. X-ray crystallography generated data about matter at a scale much smaller, and at higher resolution, than that gained using technologies of microscopic observation, for example, or mathematical or chemical methods of inferring structures. The knowledge of atomic and molecular structures afforded by X-ray crystallography therefore had a widespread impact in many fields, including chemistry and mineralogy. X-ray crystallography also aided the growth of the then-burgeoning field of molecular biology beginning in the 1930s and carrying through the postwar period[45]. The applications of X-ray crystallography investigations ranged from medical research to the industrial development of synthetic materials.

The postwar period, particularly the 1950s, saw intense activity in X-ray crystallography research. This was due in part to the honing of methods for interpreting X-ray diffraction data, the introduction of computers for aiding otherwise tedious calculations, and increased funding for science[46]. The stimulation of scientific research was part of the wide-ranging reconstruction

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[43] Baldwin.
[44] C. W. Bunn, 'Crystallography in British Industrial Laboratories', in *Fifty Years of X-ray Diffraction*, pp. 404-408.
[45] X-ray crystallographers were researching organic molecules by the 1930s. This began with X-ray crystallography research into fibres, much of which was carried out at the University of Leeds where it was supported by the local textile industry that then fuelled the city's economy. There crystallographer W.T. Astbury's X-ray investigations of wool opened up study of the protein keratin, found in hair (Astbury was one of the first to use the term 'molecular biology', in reference to biological research guided by investigations of structures). Additionally, as head of the Cavendish's Crystallography Laboratory in the 1930s, crystallographer J.D. Bernal spearheaded pioneering work on proteins and viruses. In 1934 he and Dorothy Crowfoot (later Hodgkin) produced the first X-ray crystallography images of pepsin, a protein of the 'globular' type, which represented a far more complicated subject than fibrous proteins, embarking upon another new avenue for the field that burgeoned after the war. Hall; Authier; de Chadarevian, *Designs For Life*; Olby, *The Path To The Double Helix*; Robert Olby, 'The Molecular Revolution in Biology', in *Companion to the History of Modern Science*, ed. by R. C. Olby, G. N. Cantor, J. R. R. Christie, and M.J.S. Hodge (London: Routledge, 1990), pp. 503-519.
[46] Agar; de Chadarevian, *Designs for Life*; Morris and Travis; Jenny Glusker, 'Brief History of Chemical Crystallography. II: Organic Compounds', in *Historical Atlas of Crystallography*, pp. 91-107.

efforts pursued by postwar British government policy (which also focused on housing, health and industry)[47]. After the war major crystallography laboratories, particularly those at Birkbeck and Cambridge, received funding for biological research[48]. In 1947 W.L. Bragg established a new unit for protein structure research in Cambridge, the LMB, supported by the public funding body, the Medical Research Council (MRC)[49]. Much postwar funding for X-ray crystallography was based on its projected impact on biology. The biomedical potential of X-ray crystallography had been demonstrated during the war by the elucidation of the structure of penicillin by Hodgkin in collaboration with chemist and crystallographer C.W. Bunn (aimed at aiding wartime development of synthetic penicillin)[50].

The outlines of X-ray crystallography technique

X-ray crystallography techniques were subject to constant change and variety according to research needs, material conditions and personal and local styles, but it is possible to delineate their general outlines in the postwar period: First, a crystal is either acquired or made. A sample of a biological substance that is not naturally crystalline, DNA for example, must be crystallised first. Next, a photograph is taken: X-rays are directed through the crystal and hit a photographic plate set up behind it. The arrangement of atoms inside diffracts

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[47] During the war, scientists' participation as advisors on operations and other war work advertised the idea that scientists and scientific research organisations were vital to future power struggles. The postwar governments also associated science with the promise of prosperity. 'Scientists emerged from the war keen to capitalize on their prestige', writes historian Guy Ortolano, 'and the expanding postwar state was eager to oblige'. Funding was allocated to expanding scientific education in universities (which was a postwar concern; the 1946 Barlow Report on 'Scientific Manpower' reported a shortage of scientists), civil expenditure on science increased ten times between 1945 and 1963, and industry poured more resources into scientific research (partly funded through the Department of Scientific and Industrial Research). Ortolano, p. 20. On the positions of scientists during and after the war see also David Edgerton, *Britain's War Machine: Weapons, Resources, and Experts in the Second World War* (Oxford: Oxford University Press, 2011); Edgerton, *Warfare State*; Guy Hartcup, *The Effect of Science on the Second World War* (London: Palgrave MacMillan, 2003); Tom Wilkie, *British Science and Politics Since 1945* (Oxford: Blackwell, 1991).

[48] This came from government funding bodies including the Medical Research Council (MRC) and Agricultural Research Council (ARC), as well as others such as the Nuffield Foundation.

[49] The LMB was a leading centre of structural biological research; in 1962 members Max Perutz and John Kendrew won Nobel Prizes for their protein research focusing on haemoglobin and myoglobin. De Chadarevian, *Designs for Life*.

[50] De Chadarevian, *Designs for Life*.

these rays, which register on the photographic plate as the 'diffraction pattern' or 'diffraction photograph' (Figure 6).

The diffraction photograph is not a direct image of what a molecule or atoms would 'look' like if could have been seen at this scale, but rather a registration of the interaction between X-rays and atoms. Diffraction is caused by waves moving through a slit. As X-rays pass through 'slits' between atoms (X-rays are small enough to do so, unlike visible light), their waves fan outwards on the other side (imagine the concentric ripples on a pond's surface after a pebble is thrown in). These waves, emanating from multiple spaces between atoms interfere with one another, and where they cross, they either reinforce or cancel each other out, registering as a mark or an absence on the film.

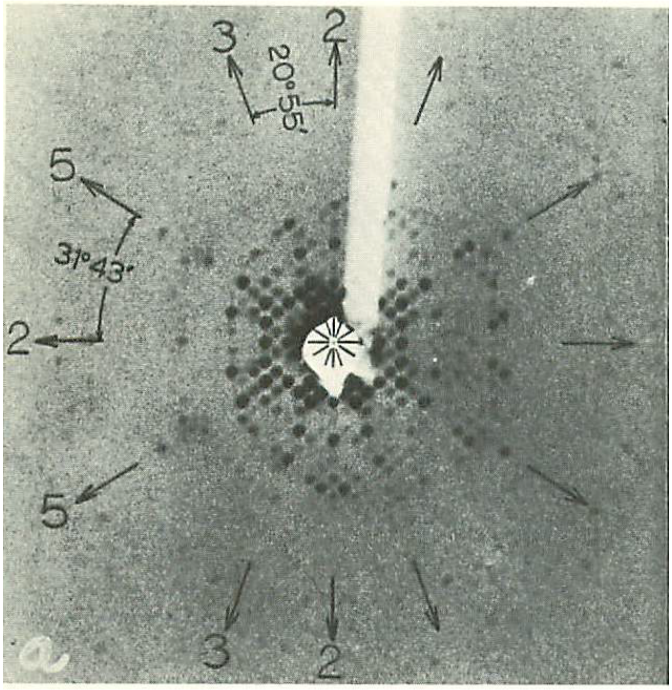

Figure 6 X-ray diffraction photograph of a crystal of poliovirus published by Aaron Klug and John Finch in 1959. The arrows marked on this photograph refer to so-called 'spikes' of high intensity registrations on the film. They relate to the scientists' analysis of the symmetry of the virus structure.

This diffraction pattern requires interpretation by the scientist in order to determine the structure of atoms that created it, a process that one crystallographer likened to confronting a 'huge crossword puzzle'[51]. 'Solving'

[51] Vladimir Vand, 'Review: A New Routine Tool?', *Science*, 136 (3512) (20 April 1962), 252 (p. 252).

the structure, as crystallographers termed it, involved mathematical calculation based on the positions and observed intensities of the marks on the photograph. Using a reference key showing visual gradations of intensity, these had to be 'estimated by eye' as Hodgkin noted in 1964[52]. Crystallographers performed calculations very tediously by hand, but more frequently with the aid of computers by the late 1950s[53]. Visualisation was crucial here: drawn diagrams and three-dimensional modelling were integral to interpreting diffraction data and to discerning features of the structure in space (discussed below).

Although these techniques comprise the backbone of crystallographic practice, they rarely accounted for the entirety of a given research effort. As Birkbeck crystallographer Alan Mackay remarked, 'half a problem may involve crystallography, and in most cases crystallographers have learned the other half of the problem to retain command of the topic as a whole'[54]. In determining structures, scientists often combined X-ray diffraction data with other kinds of data, such as chemical data about a material and data generated using other techniques and instrumentation such as electron microscopy, as in the case of the virus research I will explore later. On the variety of skills and knowledge required by X-ray crystallography, Lonsdale commented in 1953, 'Perhaps it is a pity that we call our science 'Crystallography', when it is really the study of the solid state, with all that that implies'[55].

Forms of visualisation

This section briefly introduces several forms of visualisation widely used in postwar British crystallography. Models and diagrams were vital to X-ray crystallographers' interpretation of data at this time, allowing researchers to think in rotation and to discern spatial structures. Modelling in particular saw heavy

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[52] Dorothy Crowfoot Hodgkin, 'The X-ray Analysis of Complicated Molecules', Nobel Lecture, December 11, 1964. Available at: http://www.nobelprize.org/nobel_prizes/chemistry/laureates/1964/hodgkin-lecture.pdf. Accessed 26 November 2014.

[53] On the use of computers in X-ray crystallography for performing calculations necessary to interpreting diffraction data in this period see Agar; de Chadarevian, *Designs for Life*.

[54] Alan Mackay, 'The Lab', in *Culture of Chemistry: The Best Articles on the Human Side of 20th-Century Chemistry from the Archives of the Chemical Intelligencer*, ed. by Balazs Hargittai and Istvan Hargittai (New York: Springer, 2015), pp. 113-118 (p. 116).

[55] Kathleen Lonsdale, 'The Training of Modern Crystallographers', *Acta Crystallographica*, 6 (1953), 874-875 (p. 875).

use as scientists explored more complex structures in the postwar period[56]. As has been noted in existing scholarship, X-ray crystallography visualisation employed a variety of conventions, many of which drew upon those employed in other fields (principally chemistry and mineralogy), and X-ray crystallographers developed new forms to suit new purposes as crystallographic research expanded[57]. This survey of examples of such adaptation and innovation provides background for analyses later in this chapter and in chapter two.

Several conventions used in crystallographic visualisation drew upon those used in chemistry. Ball-and-spoke models (comprising balls, representing atoms, connected by rods) were frequently used in X-ray crystallography from the time of the Braggs' early work through the postwar period (Figure 7). Since the nineteenth century, ball-and-spoke molecular models were used in chemistry[58]. Their use in crystallography, however, was somewhat different. Whereas in chemistry the rods between balls specifically signify chemical bonds between atoms, in X-ray crystallography, the ball-and-spoke model simply represents the positions of atoms in space (and may or may not indicate chemical bonds). Crystallographers thus treated ball-and-spoke modelling as a framework within which they could emphasise different features of a molecule.

[56] The extensive use of material visualisation practices in postwar crystallography was also its last gasp: the period precedes the use of computer graphics for visualising and manipulating the structures sought after by crystallographers, which phased out the heavy use of models. This technology, called 'interactive molecular graphics', was developed in the late 1960s and through the 1970s and 1980s it gradually replaced physical modelling in X-ray crystallography practice, with uses primarily in protein research. Eric Francoeur and Jerome Segal, 'From Model Kits to Interactive Graphics', in *Models: The Third Dimension of Science*, pp. 402-429.

[57] de Chadarevian, 'Models and the Making of Molecular Biology'; de Chadarevian, *Designs for Life*.

[58] Meinel; Eric Francoeur, 'The Forgotten Tool'.

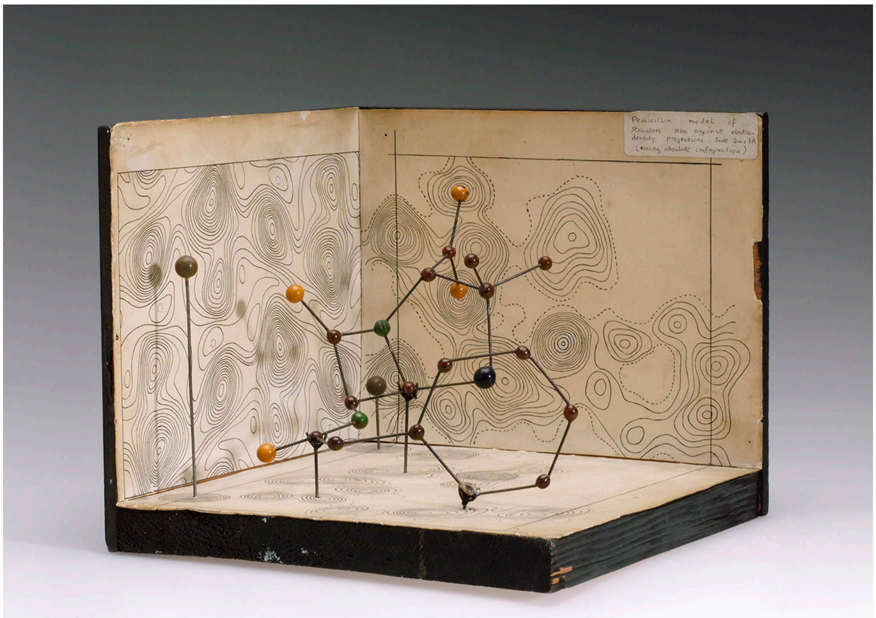

Figure 7 Molecular model of penicillin by Dorothy Hodgkin (c.1945).

Crystallographers also adapted existing conventions for drawing diagrams of molecular structures from chemistry, including two-dimensional 'ball-and-spoke' diagrams showing atomic arrangements. Schematic diagrams of atoms represented by letters in circles connected by lines indicating bonds had been used in chemistry since the 1860s when the Scottish chemist Alexander Crum Brown pioneered this design for 'graphic formulae'[59]. As with ball-and-spoke models, crystallographic diagrams do not necessarily indicate chemical bonds. This graphic format was often used in 'flat' plan drawings, showing the distances of atoms from a given horizontal plane (such as the paper itself) marked in the diagram (Figure 8).

[59] Meinel, p. 249.

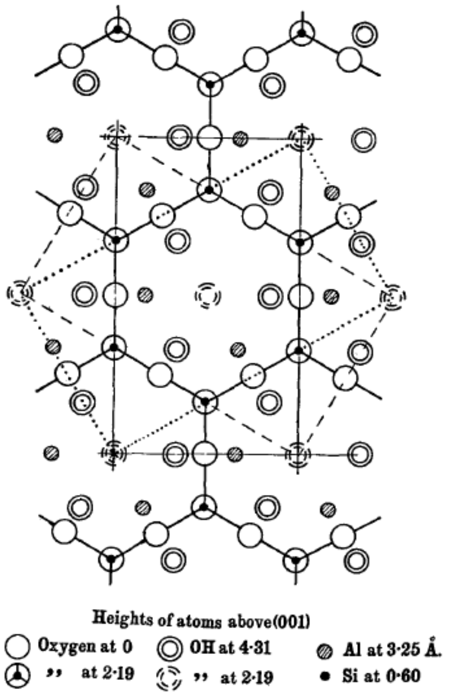

Fig. 1. Projection of the kaolinite layer on (001) showing the three possible bases for the unit cell; the cell adopted is shown in full lines.

Figure 8 Diagram of a kaolinite (clay) mineral structure using circle-and-line notation showing locations of atoms at different elevations in the structure published by British X-ray crystallographers George W. Brindley and Keith Robinson in 1946.

Postwar X-ray crystallographic visualisation also drew upon conventions used in crystallography before the advent of X-ray diffraction methods. For example, in 'close packing' models, spheres, representing atoms, are stacked layer-upon-layer in contact with each other in the closest way possible. Such models allow for experimentation with how atoms might be arranged in three-dimensions within a space defined by a given kind of symmetry. Close packing models had been used in nineteenth century crystallography to explore relationships between crystal cleavage and symmetry (see nineteenth-century chemist and crystallographer William Wollaston's octahedral close-packing model, Figure 9)[60]. The Braggs incorporated this method into X-ray crystallographic practice. The Braggs, both physicists, probably gained knowledge of modelling practices in crystallography as a result of W.L. Bragg's consultations in the early 1910s with William Pope and William Barlow, both

[60] Authier.

(pre-X-ray) crystallographers and chemists who utilised close packing models in their work[61].

Figure 9 William Wollaston's model of close-packed hard spheres (early nineteenth century).

X-ray crystallographers also adopted conventions for drawing crystal structure diagrams from those rooted in early crystallography. Beginning at the turn of the nineteenth century, crystallographers drew crystal structures geometrically in projection, as seen in late eighteenth century diagrams by the crystallographer René Just Haüy (Figure 10)[62]. Postwar X-ray crystallographers drew upon this convention, frequently representing polyhedra in projection, which allowed several crystal faces to be shown at once on a flat surface (Figure 11 shows an example of a structure published by crystallographer Helen Megaw

[61] On Bragg's consultations with Pope and Barlow see Authier and Hunter.

[62] Previously crystallographic convention involved representing individual mineral samples naturalistically. Haüy's diagrams represent a departure from this mode of rendering crystals. As historians of science Lorraine Daston and Peter Galison write, 'Despite the variations and irregularities in individual crystals, Haüy maintained that all could be reduced to "a kernel of primitive form"'. Daston and Galison, *Objectivity*, p. 64. See also James Elkins, 'Art History as the History of Crystallography', in James Elkins, *The Domain of Images* (Ithaca, New York: Cornell University Press, 2001), pp. 13-30.

in clinographic projection, in which the crystal's front and right side face the viewer). This aided explorations of symmetries and orientations of structures in space. Oxford X-ray crystallographer Michael Glazer (interviewed for this research) reports that training in this kind of projection drawing persisted even into the 1960s when he was a research student. Lonsdale, Glazer's supervisor, sent him to Birkbeck in the evenings for Alan Mackay's course in crystal drawing in projection[63].

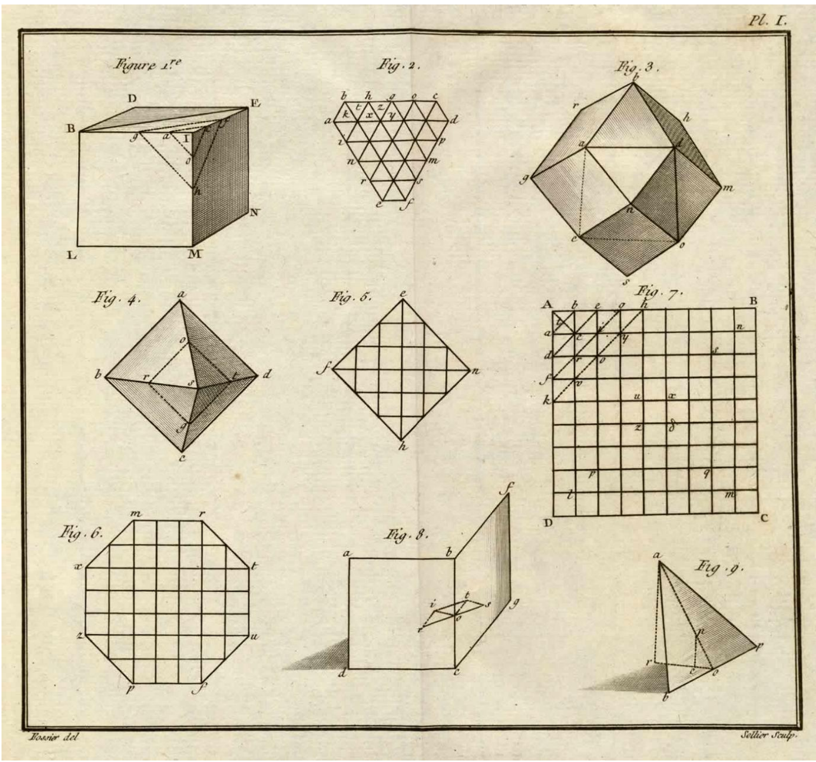

Figure 10 Geometrical diagrams of crystal structures in projection published by René Just Haüy in 1784.

[63] Interview with Michael Glazer, 29 May 2015.

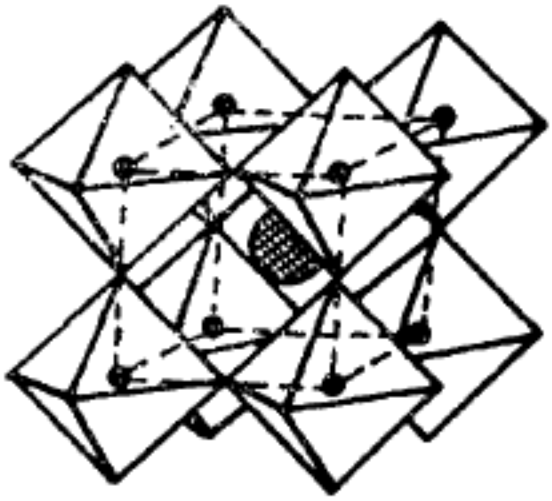

Figure 11 Crystal structure diagram of the mineral perovskite in clinographic projection published by X-ray crystallographer Helen Megaw in 1946.

In addition to adapting existing conventions to the purposes of their research, X-ray crystallographers also developed new forms of visualisation to meet the needs of new research areas as they developed. For example, to accommodate the complex molecular forms with which crystallographers of proteins contended, the LMB biochemist and crystallographer John Kendrew developed 'skeletal' models in the late 1940s, inspired in part by the construction toy Meccano[64]. They comprise intersecting thin metal rods representing bonds between atoms (Figure 12). This became a formalised and widely used format among British crystallographers determining complex structures; their 'transparent' quality allowed scientists to see several regions of intricate structures at once[65]. The necessities of protein research also underpinned crystallographers' use of space-filling models (Figure 13)[66]. These models comprise opaque wooden or plastic spheres larger than those used in ball-and-spoke modelling, with ends cut off where the 'atom' might be bonded to

[64] de Chadarevian, 'Models and the Making of Molecular Biology'.
[65] Francoeur, 'Molecular Models and the Articulation of Structural Constraints in Chemistry', p. 100.
[66] The idea of the space-filling model was conceived in the 1930s by both the American crystallographer Edward Mack and the French chemist Michel Magat (independently of one another), although Magat did not build any space-filling models. Francoeur, 'Molecular Models and the Articulation of Structural Constraints in Chemistry'.

another[67]. These suited investigations of the folds of amino acid chains that form proteins.

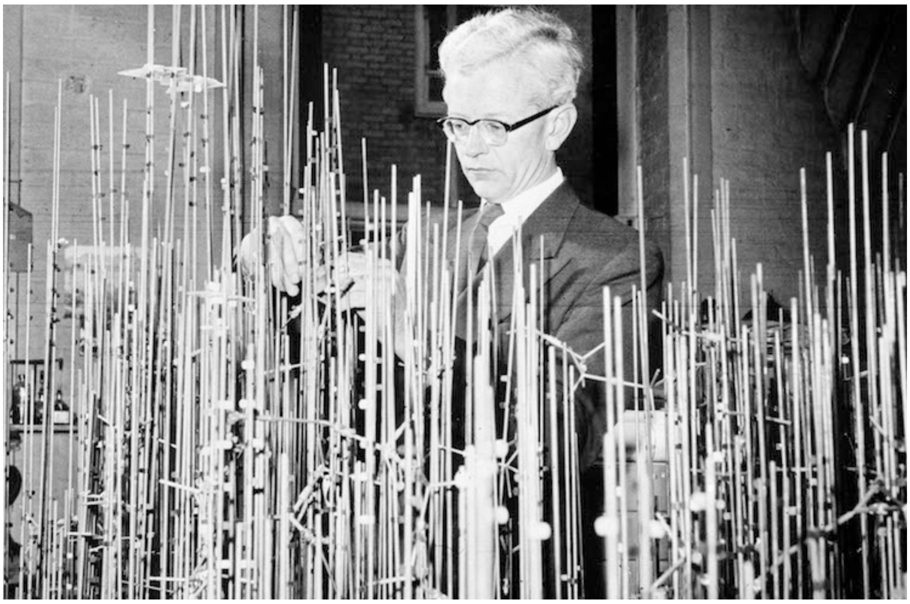

Figure 12 John Kendrew constructing a skeletal model of myoglobin, a protein found in some muscle tissue (the model was dubbed the 'forest of rods') (c. 1960).

Figure 13 Space-filling model of ethanol made with components from the Courtauld Atomic Model Set produced by the London firm Griffin and George in the 1950s.

Crystallographers also developed several two-dimensional diagrammatic conventions for the interpretation of diffraction data. Patterson maps, which show distances between atoms, are an example. These are based on calculations

[67] Space-filling models were constructed as such to afford a greater sense of the space taken up by an atom, and allowed researchers to test the effects of large volumes of atoms on the shape of the molecule (known as 'steric hindrance'). Francoeur, 'Molecular Models and the Articulation of Structural Constraints in Chemistry', p. 99.

made in interpreting a diffraction photograph using a function described by the crystallographer Arthur Lindo Patterson in 1934. Patterson's function allowed scientists to calculate distances between atoms in a structure even without knowledge of the phase at which an X-ray wave contacted the photographic film (Figure 14). This method became useful in determining structures of large organic molecules[68].

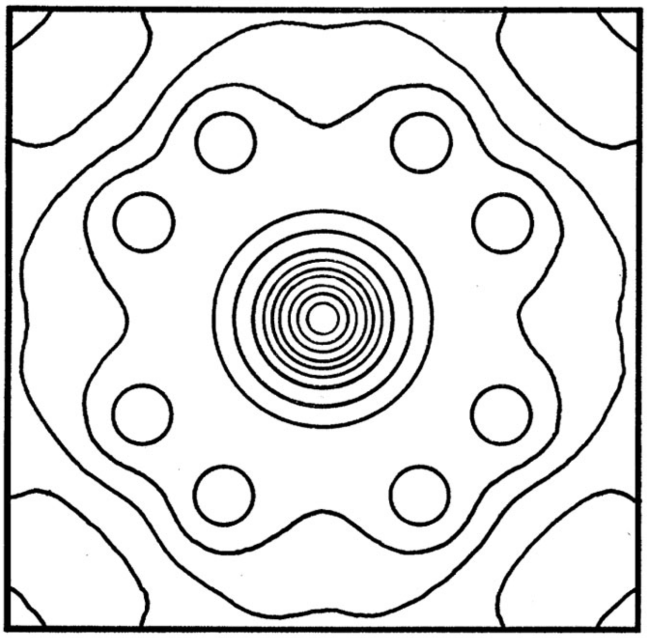

Figure 14 Patterson map (reflecting data on potassium dihydrogen phosphate) published by Arthur Lindo Patterson in 1934.

The electron density map is another form of diagram developed by an X-ray crystallographer to suit particular techniques and research subjects in the field. First published by W.L. Bragg in 1929, electron density maps straddle the boundary between diagram and three-dimensional model[69]. They resemble topographical contour maps, only their contours plot the probability of finding an electron at a given location (clusters of electrons indicate probable atom locations). Postwar crystallographers produced electron density maps on transparent Perspex or paper sheets (Figure 15), with multiple sheets created for a given structure, each one referring to a specific elevation in it. These sheets

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[68] *Historical Atlas of Crystallography*.
[69] De Chadarevian, *Designs for Life*. The paper showing Bragg's electron density maps is W. Lawrence Bragg, 'The Determination of Parameters in Crystal Structures by Means of Fourier Series', *Proceedings of the Royal Society of London A*, 123 (792) (1929), 537-559.

were then stacked one upon the other, approximating a three-dimensional structure that would then be plotted more clearly using modelling materials such as ‘skeletal’ rods or balls-and-spokes.

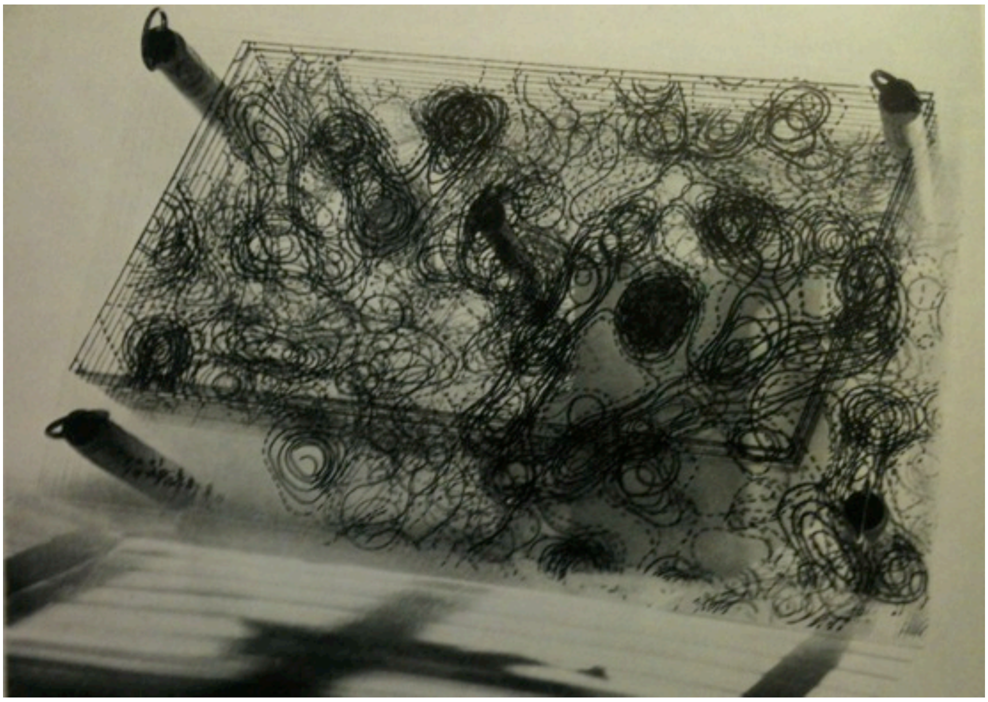

Figure 15 Example of an electron density map relating to research on the structure of myoglobin by John Kendrew.

This brief survey describes a number of basic formats within which postwar crystallographers worked in order to visualise structural data. It is not, however, inclusive of the full scope and variety of crystallographic visualisation and its uses in the period. Many of the forms enumerated above are associated with so-called ‘direct’ methods of researching structures, meaning they might rely solely on X-ray crystallography data. The example of virus modelling, explored in the next section, differs in some ways from the conventions and uses of visualisation described here (it is not the result of ‘direct’ methods, for example) and thus moves beyond the class of conventions typically associated with postwar X-ray crystallography research. It therefore offers a more variegated picture of X-ray crystallographic visualisation in the period, while also allowing for more in-depth exploration of themes raised in this section, such as the development of new forms to suit a given research project and the adaptation of practices from outside the field.

2. Building viruses

This section discusses Klug and Caspar's virus structure research, focusing on their use of the Geodestix construction toy to visualise virus structures. This example highlights material and social contingencies shaping the form and use of crystallographic visualisations, contributes empirical information on the materiality of visualisation practices in the field, and identifies crystallographic visualisation as a process productively examined through the lens of craft scholarship from the history of design. This example both frames and complicates a picture of postwar British X-ray crystallographic visualisation practice more broadly. This case also points to the social networks enabling communication between postwar British X-ray crystallographers and those active in design.

Postwar virus crystallography

The postwar period saw intense research into virus structures using crystallography in Britain, especially at Birkbeck's Crystallography Department[70]. Working out virus structures was important because it aided research on virus function. Klug and Caspar's virus research, with which this chapter is concerned, focused on the structure of the virus capsid or 'shell', which encases the virus's nucleic acid – its genetic material and infective agent[71]. Pre-war X-ray crystallography research had argued that the shell is composed of regular identical protein subunits, and much subsequent research concerned their structure and arrangement[72].

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[70] Detailed accounts of virus crystallography in the period, which this research builds upon, are provided by Creager and Morgan, 'After the Double Helix'; Gregory J. Morgan, 'Early Theories of Virus Structure', in *Conformational Proteomics of Macromolecular Architectures*, ed. by R. Holland Cheng and Lena Hammar (Toh Tuck Link, Singapore: World Scientific, 2004), pp. 3-40.
[71] Crystallographers' structural investigations of viruses were in some respects part of a larger strand of postwar molecular biology research into relationships between nucleic acid and proteins (also explored in DNA research). This emphasis meant that some of DNA's key researchers, including Franklin, Crick and Watson, were central players in early virus crystallography. Creager and Morgan, 'After the Double Helix'.
[72] Bernal and US crystallographer Isidor Fankuchen collaborated on X-ray diffraction research in the early 1940s that indicated that viruses were composed of many regular subunits or 'submolecules' as they called them. Creager and Morgan, 'After the Double Helix', p. 243.

Klug began researching virus structure in 1954 with Rosalind Franklin at Birkbeck's Crystallography Department, which he had joined the previous year. Franklin had arrived earlier in 1953 from Kings College (where she had taken X-ray photographs of DNA), and began researching tobacco mosaic virus (TMV)[73]. Klug and Franklin collaborated on plant viruses and, beginning in 1957, poliovirus (research that Klug continued after Franklin's death in 1958). This structural research at times involved building models of virus shells, often with subunits represented by ping-pong balls (Figure 16) (available evidence does not offer insights on whether these models served a heuristic function integral to research or were primarily in aid of the cognition or communication of data). The models speak to a packing problem: how to arrange units in a defined space?

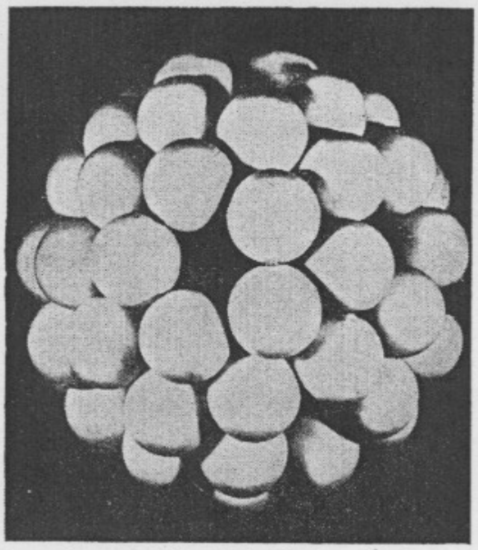

Fig. 4. Schematic model of a likely arrangement of the sixty identical structural sub-units forming the protein 'shell' of the poliovirus particle (cf. ref. 8). The actual appearance of the virus particle will depend on the precise arrangement adopted and on the shape of the sub-unit, which are not known. The diameter of a sub-unit is about 60–65 A.

Figure 16 Image of a poliovirus model published by Klug and the crystallographer John Finch in 1959.

In the late 1950s, Klug began collaborating with one of the few US virus crystallographers working at the time, biophysicist Donald Caspar of Caltech and

[73] Her initial research consisted in taking X-ray diffraction photographs of TMV and interpreting them using the Patterson function (mentioned earlier) to determine if the virus had a helical structure, which had recently been suggested by Watson, then at Caltech. Creager and Morgan, 'After the Double Helix'.

later Harvard[74]. British virus crystallographers were in frequent communication with Caspar and he was integrated into British circles of crystallographers working on biological molecules ('He used to visit fairly regularly', recalled Klug[75]). In 1955, he worked at Cambridge and in 1958 worked for a time at Birkbeck's Crystallography Department[76].

A 'structural paradox'

The case here concerns Klug and Caspar's research into so-called 'spherical' viruses, which included the poliovirus[77]. In their study of the spherical virus shell's protein subunits, Caspar and Klug encountered what they called in a 1962 paper a 'structural paradox'[78]. This emerged from the combination of experimental evidence from X-ray crystallography and electron microscopy[79]. The data from X-ray crystallography research provided information on the symmetry of spherical viruses. In 1956 James Watson and Francis Crick suggested they possessed a cubic kind of symmetry[80]. Of the three types of cubic symmetry, tetrahedral, octahedral and icosahedral, recent X-ray investigations by Klug, Caspar and their colleagues indicated that these viruses possessed icosahedral symmetry[81]. The icosahedron, one of the five Platonic solids, is made

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[74] Collaboration between the Birkbeck virus researchers and Caspar resulted in a 1959 paper: R. Franklin, A. Klug and D.L.D. Caspar, 'The Structure of Viruses as Determined by X-ray Diffraction', in *Plant Pathology: Problems and Progress 1908-1958*, ed. by C.S. Holton and others (Madison: University of Wisconsin Press, 1959), pp. 5-13, cited in Morgan, 'Early Theories'.
[75] Aaron Klug interviewed by Tony Crowther and John Finch about his life and work, December 2001, DVD. MRC LMB Archive.
[76] 'Don Caspar on Rosalind Franklin', CSH Oral History Collection, 1 January 2001, online video recording. Available at http://library.cshl.edu/oralhistory/interview/scientific-experience/women-science/rosalind-franklin/. Accessed 15 June 2015.
[77] Viruses can be distinguished roughly by different shape-based categories. 'Spherical' viruses are not perfectly round, but they are identified as such to distinguish their roughly spherical polyhedral form from 'rod-shaped' viruses such as tobacco mosaic virus.
[78] D.L.D. Caspar and A. Klug, 'Physical Principles in the Construction of Regular Viruses', *Symposia on Quantitative Biology: Basic Mechanisms in Animal Virus Biology*, *Volume 27* (Cold Spring Harbor, New York: 1962), 1-22 (p. 9).
[79] Caspar and Klug, 'Physical Principles'. Gregory Morgan's excellent archival research on this subject provides a detailed account of Klug and Caspar's virus research (although modelling is not a subject of his analyses). See Gregory Morgan, 'Early Theories'; Gregory Morgan, 'Virus Design, 1955-1962: Science Meets Art', *Phytopathology*, 96 (2006), 1287-1291.
[80] F.H.C. Crick and J.D. Watson, 'Structure of Small Viruses', *Nature*, 10 March 1956, 473-475.
[81] Caspar and Klug's 1962 paper reviews recent X-ray investigations by Caspar, Finch and Klug indicating 'icosahedral symmetry is present down to the molecular level in a substantial proportion of the particle' (Caspar and Klug, 'Physical Principles', p. 9). Icosahedral symmetry was indicated by X-ray crystallography investigations by Klug and Finch on poliovirus, by

up of twenty congruent triangular faces (Figure 17). This particular symmetry would provide the most economical way for a spherical virus to hold the greatest possible amount of nucleic acid, they surmised[82]. Icosahedral symmetry demands that the virus shell must have 60 or a multiple of 60 identical subunits (and chemical data suggested the subunits were identical)[83].

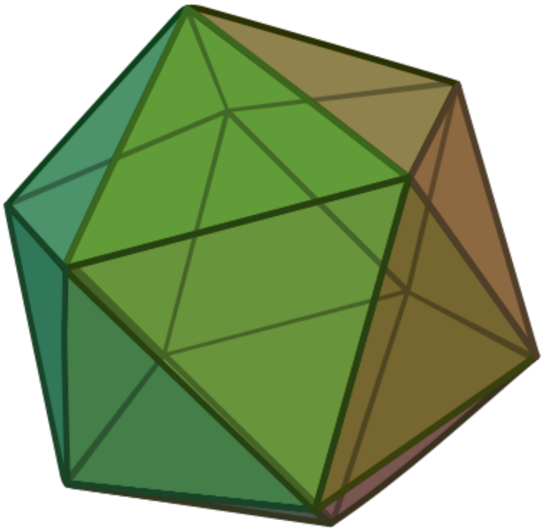

Figure 17 Icosahedron.

Caspar and Klug were aware of recent electron microscopy studies by other scientists, however, that had shown that the number of protein subunits encasing spherical viruses was 'never 60 or a multiple of 60, and in most cases it is greater than 60'[84]. Electron microscopy is a method of imaging that was applied to viruses at the end of the 1950s. It produced images of the external forms of viruses (Figure 18). Electron microscopy, however, supplied structural information at lower resolution than X-ray crystallography, and did not supply data on symmetry as crystallography did. Given that X-ray crystallography data

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Caspar on tomato bushy stunt virus, and by Klug, Finch and Franklin on turnip yellow mosaic virus. Donald Caspar, 'Structure of Bushy Stunt Virus', *Nature*, 10 March 1956, 475-476; Aaron Klug, John Finch and Rosalind Franklin, 'The Structure of Turnip Yellow Mosaic Virus: X-Ray Diffraction Studies', *Biochimica et Biophysica Acta*, 25 (1957), 242-252; John Finch and Aaron Klug, 'Structure of Poliomyelitis Virus', *Nature*, 20 June 1959, 1709-1714.

[82] Caspar and Klug, 'Physical Principles'.

[83] As Caspar and Klug wrote, 'it is impossible to put more than 60 identical units on the surface of a sphere in such a way that each is identically situated'. Caspar and Klug, 'Physical Principles', pp. 9-10.

[84] Caspar and Klug, 'Physical Principles', p. 9.

on the subject indicated icosahedral symmetry (which demanded that the shell comprise 60 subunits) down to the virus's 'molecular level', the scientists were presented with what they called a 'paradox'[85]. From the geometrical point of view it seemed like an intractable problem.

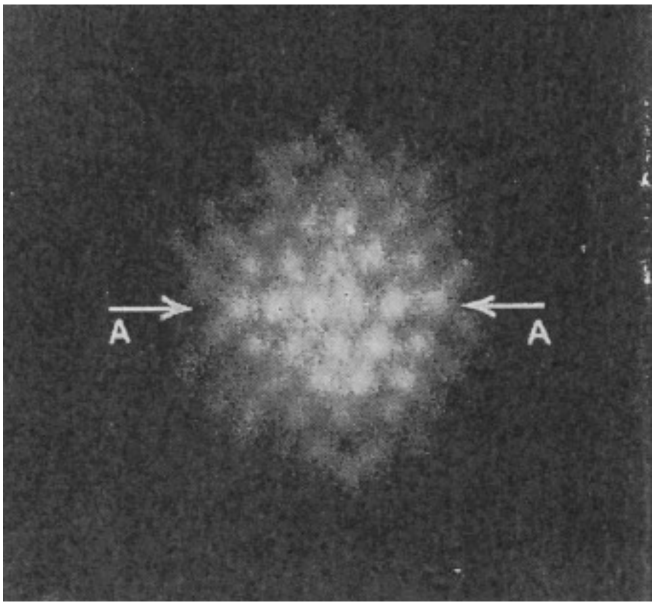


Figure 18 A 1961 electron microscope image of a particle of the adenovirus.

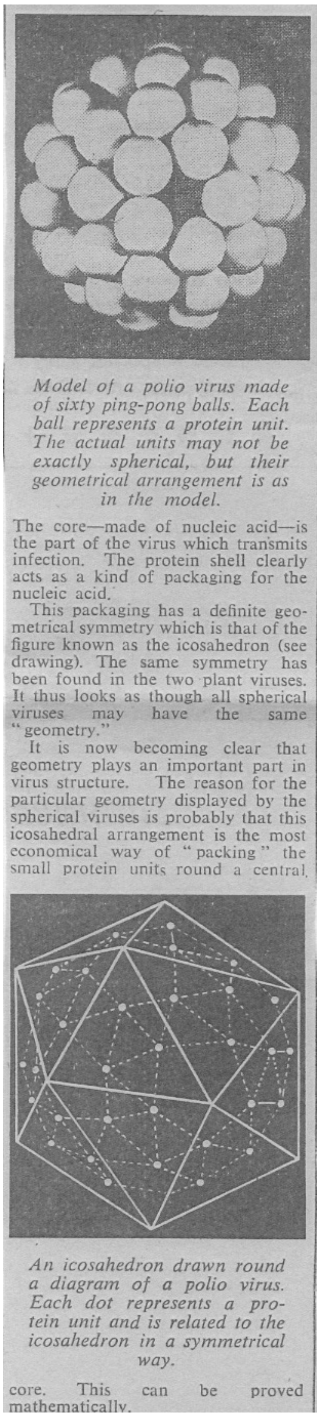
Cross-field exchange

> In Bucky's recent forays into his synergetic universe of spherical closest-packing geometries, he has found himself face to face with protein biochemists who have got into the same territory from the other end and with quite other motives.
>
> Reyner Banham, 'The Dymaxicrat', 1963[86]

A way out of this problem emerged through the researchers' interaction with Buckminster Fuller. In 1959 the British artist John McHale, after reading about Klug's poliovirus research, put Klug in contact with Fuller. McHale had noticed a resemblance between the poliovirus's icosahedral form and Fuller's geodesic domes. Klug's research had received newspaper coverage because it concerned

[85] Ibid.
[86] Reyner Banham, 'The Dymaxicrat', in *A Critic Writes: Essays By Reyner Banham*, ed. by Mary Banham (Berkeley: University of California Press, 1996), pp. 91-95 (p. 92). Originally published in *Arts Magazine*, 38 (October 1963), 66-69.

polio[87] (the threat of polio epidemics had only recently begun to decline). The *Observer*, for example, printed an article including an image of a ping-pong ball model of the virus and associated diagram of an icosahedron (Figure 19)[88].



Model of a polio virus made of sixty ping-pong balls. Each ball represents a protein unit. The actual units may not be exactly spherical, but their geometrical arrangement is as in the model.

The core—made of nucleic acid—is the part of the virus which transmits infection. The protein shell clearly acts as a kind of packaging for the nucleic acid.

This packaging has a definite geometrical symmetry which is that of the figure known as the icosahedron (see drawing). The same symmetry has been found in the two plant viruses. It thus looks as though all spherical viruses may have the same "geometry."

It is now becoming clear that geometry plays an important part in virus structure. The reason for the particular geometry displayed by the spherical viruses is probably that this icosahedral arrangement is the most economical way of "packing" the small protein units round a central

An icosahedron drawn round a diagram of a polio virus. Each dot represents a protein unit and is related to the icosahedron in a symmetrical way.

core. This can be proved mathematically.

Figure 19 Segment of a 1959 *Observer* article on Klug's poliovirus research.

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87 Morgan, 'Early Theories'; Robert W. Marks, *The Dymaxion World of Buckminster Fuller* (Carbondale, Illinois: Southern Illinois University, 1960).

88 Scientific Correspondent, 'New Light on How Polio Starts', *Observer*, 21 June 1959. This article is also cited in Morgan, 'Early Theories'.

Before describing Fuller's effect on Klug and Caspar's work, I will pause to examine the way they were brought together, as it bears on this thesis's research into cultural transmission between crystallography and design fields. The initial contact between Klug and Fuller emerged from a culture of cross-field exchange among specific networks of practitioners in science, design and art through which ideas, objects and texts circulated in this period (as delineated further in the next chapter). John McHale, the catalyst for the relationship between Klug and Fuller, was involved in these networks. McHale was a member of the circle of London-based artists, designers, architects and critics known as the Independent Group (IG), who participated in these networks[89]. Members of the IG, especially McHale and the architecture critic Reyner Banham, were some of Fuller's earliest champions[90].

McHale's observation of the resemblance between Fuller's domes and Klug's poliovirus model – and his interest in contemporary scientific research that this exhibits - typified the interest in nature's structures among designers and artists in his social circles. Ideas on science animating the work of many designers and artists in his milieu were inflected by their personal relationships with scientists and engagement with current scientific concepts. In particular, at this time several members of the IG drew upon biologist D'Arcy Wentworth Thompson's book *On Growth and Form*[91]. Originally published in 1917, a second edition of *On Growth and Form* came out in 1942, which circulated among designers, architects, artists and scientist during and after the war[92].

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[89] Associated with the advent of Pop Art, the IG evinced an analytical take on contemporary British culture – from the consumption of American popular culture and debates around urban planning to scientific and technological innovations. On the IG see Anne Massey, *The Independent Group: Modernism and Mass Culture in Britain, 1945-59* (Manchester: Manchester University Press, 1995); *The Independent Group: Postwar Britain and the Aesthetics of Plenty*, ed. by David Robbins (Cambridge: MIT Press, 1990).

[90] They, like Fuller, maintained a critical position toward modernist architecture and design establishments. Although Fuller is most commonly associated with architecture, and geodesic domes particularly, he was neither trained nor, for most of his career, licenced as an architect, and was largely positioned outside contemporary architecture circles. Banham and McHale, however, championed Fuller's work, and Banham lauded Fuller in his history of modernism, *Theory and Design in the First Machine Age*, as embodying the technological futurist ideals that Banham saw as only realised through surface appearance in modernist architecture. McHale, who was trained as a sociologist, collaborated with Fuller on several of Fuller's social projects concerning global resources and also wrote a book on Fuller in 1962. McHale; Reyner Banham, *Theory and Design in the First Machine Age* (London: The Architectural Press, 1977 [1960]).

[91] D'Arcy Wentworth Thompson, *On Growth and Form* (Cambridge: Cambridge University Press, 1961).

[92] Chapter two provides further details on the circulation of this book.

Thompson's book is a detailed, mathematical exploration of recurring morphologies across animate and inanimate nature that privileges mathematical laws and physical forces over heredity in the origin of natural forms[93]. His reading of Thompson's book probably prompted McHale's identification of and interest in possible similarities between Klug's poliovirus model and Fuller's domes. *On Growth and Form*'s understanding of biological structures in terms of mathematics and engineering chimed with the approach of the virus researchers discussed here as well. For example, Caspar, Klug, Crick and Watson cite Thompson in papers on the symmetry of virus shells[94].

Klug and Fuller's joint television appearance can also be traced back to the circulation of *On Growth and Form*. The working title for the *Horizon* episode discussed here was 'Structure and Form', because it was based on Thompson's book, and Klug and Fuller were chosen to appear because their exchange about architectural and virus structure, and their individual practices, embodied concepts associated with it[95]. The book's circulation among postwar science networks included those of science writers and producers who worked on the programme, such as its main producer Ramsay Short (who originally trained as an architect in fact). This indicates that even the source used in this chapter is closely intertwined with cross-disciplinary networks of communication and shared interest from which the case itself emanates.

McHale's observation was correct, in that there was indeed a parallel between Fuller's domes and the structure of spherical viruses. Fuller's geodesic domes, first built in 1949, are typically constructed of metal struts arranged in

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[93] His ideas were somewhat idiosyncratic in the context of dominant biological paradigms at the time, because they are not framed by Darwinian ideas, although they do not conflict with them directly either.

[94] For example, Caspar and Klug wrote that although electron microscopy showed that some viruses appeared to be regular icosahedra, this does not necessarily mean that their 'symmetry down to the molecular level is also icosahedral', citing Thompson's observation that 'various Radiolarians…with highly symmetrical skeletons are probably not built of a regular array of silica units' (Caspar and Klug, 'Physical Principles', p. 8). Additionally, Watson and Crick, arguing that there are a limited number of ways to build a spherical virus shell possessing cubic symmetry also turned to Thompson: 'The point is very well stated in D'Arcy Thompson's "On Growth and Form", in which we find "the broad, general principle that we cannot group as we please any number and sort of polygons into a polyhedron, but that the number and kind of facets in the latter is strictly limited to a narrow range of possibilities"'. Crick and Watson, 'Structure of Small Viruses', p. 474.

[95] Boon, ''The Televising of Science is a Process of Television''.

triangles, often on the basis of the icosahedron, in which its twenty faces are further subdivided into triangles (Figure 20)[96]. Their form was designed to encase the most possible space using the fewest resources. This reflects the drive for efficiency that characterised much of Fuller's work. Although he looked to standardisation and industrial technologies in response to social concerns, much like modernist architects such as Le Corbusier, he criticised their work as concerned with surface appearance, having only the look of engineering and industrial technologies[97]. Fuller claimed to be unconcerned with aesthetics, and maintained that the form of his designs emerged from his aim of meeting social needs (particularly housing) efficiently[98].

For Klug, Fuller's geodesic domes provided clues to a way out of the 'structural paradox' he and Caspar encountered when it came it virus structure[99]. In 1960, when the first book on Fuller was published, Fuller sent it to Klug [100]. Looking at the geodesic domes pictured inside, Klug noted that they evidenced a similar kind of packing arrangement to that of the virus shell - only they departed from the strict equivalence demanded by the geometrically perfect icosahedron[101]. This helped Klug arrive at the solution to the question of virus structure, the idea he called 'non-equivalence' – basically that viruses were not

[96] Fuller had only recently achieved wide international attention in the mid-1950s, as a result of several high-profile uses of his geodesic domes. These include Cold War propaganda and military uses such as a geodesic dome that served as the US pavilion at a 1956 international trade fair in Kabul, Afghanistan, another at the 1959 Moscow Trade Fair, and Fuller's radar-detecting 'radomes' constructed north of the Arctic Circle as an early-warning system against air attack on the US.
[97] Michael John Gorman, *Buckminster Fuller: Designing for Mobility* (Milan: Skira, 2005).
[98] Fuller's first house design, the 'Dymaxion House' (1927), was conceived with efficient functioning and construction in mind (McHale wrote that it was 'designed to be air-delivered by a dirigible […] and erected in one day'). Such themes carried through much of his work. To achieve his goals, Fuller drew upon new technologies as well as naturally occurring forms and geometries. His own close packing explorations, for instance, underpinned the forms of his geodesic structures. Gorman; John McHale, *R. Buckminster Fuller* (London: Prentice Hall, 1962), p. 16.
[99] Aaron Klug interviewed by Tony Crowther and John Finch.
[100] Marks.
[101] Like spherical virus shells, geodesic domes appear to comprise too many subunits (in this case, triangular aluminium strut components). Klug thought, looking at the domes, that their triangular units were held together by 'strings' joined by 'little wheels', which would allow for slight movement and adjustment in the structure, thus allowing them to depart from strict icosahedral symmetry. This was actually not the case; they did depart from the strict equivalence demanded by strict icosahedral symmetry, but it was because they varied in shape slightly. This minor misunderstanding, however, did not affect the overall outcome of Klug's observation of Fuller's domes. Aaron Klug interviewed by Tony Crowther and John Finch.

perfect icosahedra, just like Fuller's domes[102]. In a 1962 article announcing these findings, Klug and Caspar included a photograph of one of Fuller's domes and compared it to the virus (Figure 20).

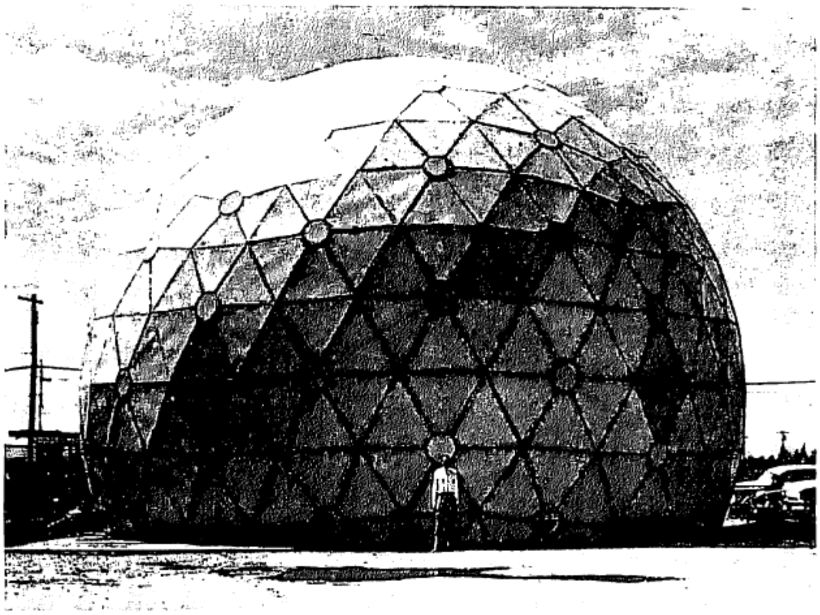

FIGURE 5. A Fuller geodesic dome (Radome designed by Geometrics, Inc., Cambridge, Mass.). Note that the surface is made up of quasi-equivalent triangles and that these are grouped in hexamers and pentamers about the small rings of the dome. (Photograph supplied by W. H. Wainwright).

Figure 20 Image of a Fuller geodesic dome as a figure in Caspar and Klug's 1962 paper.

It is rare for a scientific article to reference a non-scientific subject so explicitly, so this episode in the history of science has been commented upon before[103]. But the material dimensions of Klug and Caspar's research and their exchange with Fuller, specifically related to their thinking through hand-held models, have not been fully explored. I am able to do so by introducing a new source to the story: Klug's television appearance.

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[102] 'The solution we have found [that is, quasi-equivalence] was, in fact, inspired by the geometrical principles applied by Buckminster Fuller in the construction of geodesic domes'. Caspar and Klug, 'Physical Principles', p. 10.

[103] Nancy Anderson, 'Visual Models and Scientific Breakthroughs: The Virus and the Geodesic Dome: Pattern, Production, Abstraction, and the Ready-Made Model', in *A History of Visual Culture: Western Civilization from the 18th to the 21st Century* (Oxford: Berg, 2011), ed. by Jane Kromm, Susan Benforado Bakewell, pp, 117-130; Morgan, 'Early Theories'; 'Virus Design'. Aspects of this story are also recounted in Andrew Brown's biography of J.D. Bernal in the context of biological research carried out by Bernal's crystallography group at Birkbeck.

Models on air

I now turn my attention to the *Horizon* episode, 'The World of Buckminster Fuller'[104]. The programme and its character as a source for this research require introduction. I contend that postwar science television provides documentation of postwar crystallographers' interactions with models that is useful for the historian of crystallographic visualisation. Crystallography models appeared on several early BBC science programmes that aired between the late 1950s and early 1960s, particularly in relation to new research in molecular biology conducted by crystallographers at the time[105]. Several programmes from this era show models in use in a way other primary sources do not: that is, in motion as scientists manipulated them.

*Horizo*n is especially useful because it eschewed didactic demonstration; its angle was social and cultural - concentrating on individual scientists, their personalities, ideas, and on discussion between scientists and non-scientists[106]. A 1964 *Horizon* press release read:

> The sort of conversation which springs up when a scientist and a non-scientific friend get talking over a beer, a coffee or a glass of after dinner brandy, represents the sort of discussion we aim at[107].

Klug and Fullers' interactions on *Horizon* reflect this. The footage analysed here is not comparable to an ethnographic record of laboratory practice, of course, but in the absence of such, I argue it is the next best thing. Their conversation and interactions with models lack the qualities of a didactic demonstration enacted purely for the cameras. For example, Klug uses much scientific jargon, suggesting he is not behaving very differently for the programme than he might

[104] 'The World Of Buckminster Fuller'.

[105] Crystallography models appeared on several BBC programmes including, in addition to *Horizon*, *Eye on Research* (1957-1961). The public display of crystallography models is a subject explored in its own right in chapter three. On the appearances of X-ray crystallography models on postwar science television, see also de Chadarevian, 'Models and the Making of Molecular Biology' and *Designs for Life*.

[106] Fuller was chosen as the subject of an episode because the programme emphasised an interdisciplinary, cultural angle on science, and was in fact modelled on the arts magazine programme *Monitor*. Boon, ''The Televising of Science is a Process of Television''.

[107] This was written by Gordon Rattray Taylor, a frequent BBC science programme contributor and *Horizon* editor. Gordon Rattray Taylor, 'Science for all' [press release], 17 November 1964, cited in Boon, ''The Televising of Science is a Process of Television'', p. 114.

otherwise. Klug was not a scientist-presenter, and did not act like one. The programme's social angle thus coincides with aspects of my methodology, making it a revealing source[108].

Geodestix in motion

Much of the conversation between Klug and Fuller on *Horizon* centres on modelling. This section details selections of their exchange and their associated on-air manipulation of models. These aid this chapter's evidence-based exploration of the material interaction between the scientist and materials of visualisation, and reveal this practice as a craft process, best examined through the lens of craft scholarship.

During their conversation broadcast on *Horizon*, Klug picks up a model made of thin vinyl rods and small plastic asterisk-shaped connectors, saying to Fuller, 'This model here...You'll recognise it's your own D-stix we use?'[109]. The model is made of Geodestix (also called 'D-stix'), a toy associated with Fuller, which he used for modelling in his own work and teaching. It was also marketed as an educational toy for children (Figure 21)[110]. Caspar had brought Geodestix into the scientists' virus research, probably as a result of the fact that he too developed a correspondence with Fuller after reading the book that influenced Klug's thinking[111].

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[108] Boon also notes the parallels between current scholarship on science and the ethos of *Horizon* in these early years, which, he writes, 'share common cause in our mutual concern with the social rootedness of science'. Boon, ''The Televising of Science is a Process of Television'', p. 121.
[109] 'The World Of Buckminster Fuller'.
[110] Geodestix were produced commercially by Geodestix of Spokane, Washington, USA. Patricia Davidson, 'An Annotated Bibliography of Suggested Manipulative Devices', *The Arithmetic Teacher*, 15 (6) (October 1968), 509-524.
[111] In 1962 Caspar and Fuller met in person when Fuller was a Visiting Professor at Harvard. Morgan, 'Early Theories'.

Figure 21 Geodestix packaging c. 1959.

During their discussion, Klug starts building with Geodestix components on air. He makes equilateral triangles, which represent the protein subunits of the virus shell. Two subunits attached to one another makes a 'dimer', he says (a term describing two bonded proteins)[112]. He continues to three, four, five subunits. 'You start building out, you get an extended net', he says. Then Klug remarks, with a completed spherical model, constructed out of Geodestix, in his hands, 'when you put the angles right, it will fold up into this'[113]. He squeezes the spherical model so it contracts and expands in his hand[114]. As he does so it distorts slightly then springs back. Fuller squeezes it too and the two men admire its flexibility. As I explain below, there is a significance to this gesture of squeezing.

Some background here is required. Given the available evidence, it is difficult to pinpoint the exact stage at which Caspar and Klug used Geodestix in their research, the toy's precise role in comparison to other research methods and relative importance for each of the two collaborators in advancing their thinking (an unavoidable product of collaborative research). In a 1980 paper that reviews this research, however, Caspar suggests Geodestix were used in the process of determining how a curved surface might be constructed given Klug's theory of quasi-equivalence and how energy is distributed throughout the virus shell's surface[115]. In a 2005 interview Klug also noted that models were used at this stage as they explored what he called 'a physical principle': the viruses, he said, 'are built to minimise the energy and you can do this provided you can close a structure. And I made all sorts of models and so did Caspar showing how you could build in curvature [in such icosahedral structures]'[116].

The researchers sought a structure that was as simple to construct as possible, that is, one representing the lowest possible energy state of a spherical arrangement of subunits. One of Klug and Caspar's arguments of their 1962

[112] 'Dimer' is an example of Klug's use of obscure (to the layperson) scientific terminology on the television programme that suggests his unselfconscious behavior before the cameras; many of his descriptions and reflections do not seem to be wholly filtered for a lay audience, as might occur on science television today.
[113] 'The World Of Buckminster Fuller'.
[114] This parallels the properties of the molecule known as a 'Buckyball', identified decades later, which also returns to its original shape after it is squeezed. 'Buckyball' refers to the molecule made up of 60 carbon atoms, which was named Buckminsterfullerene (because of its resemblance to geodesic domes) in 1985.
[115] D.L.D. Caspar, 'Movement and Self-Control in Protein Assemblies: Quasi-Equivalence Revisited', *Biophysical Journal*, 32 (1980), 103-138.
[116] Aaron Klug interviewed by Ken Holmes and John Finch, 'Discovering the Structural Rules for Spherical Shell Viruses', *Web of Stories*, July 2005, online video recording. Available at http://www.webofstories.com/play/aaron.klug/20. Accessed 24 May 2015.

paper was that the virus self-assembles, in ‘a process akin to crystallization’[117]. Their concept of self-assembly implies ease of construction. On *Horizon*, Klug said they followed a conviction of Francis Crick’s about the fundamental simplicity of virus assembly: ‘He always said as a joke, that when we know that it’s a virus, a child will be able to build it’[118].

The Geodestix allowed the scientists to imagine their process of building with plastic straws as the virus’s process of building itself. Klug performed both processes on the programme as he built up the shell with Geodestix. Geodestix sticks are colour-coded; colour-coded end to matching colour-coded end builds geometric forms. ‘You join red to red and green to green’, Klug said as he built up equilateral triangles on *Horizon*[119]. Geodestix served the goal of producing a simple structure in this way (although the process nevertheless involved much indeterminacy; there are numerous possibilities for the kinds of structures one might build).

When a form was constructed that met criteria they theorised to hold for the virus, they would know when they saw it - and squeezed it. If the model returns to its initial form after squeezing, that is indication that the form is in its lowest energy state. After Klug squeezes the model during the conversation on *Horizon*, Fuller remarks:

> ‘The elasticity of your model makes up for spherical trigonometry’.
>
> ‘You don’t have to do any calculation’, agrees Klug, ‘That’s the marvellous thing about it. People often ask me, can you do spherical trig? Well yes, but I don’t use it’[120].

This statement points to Klug’s trust in material modelling as an empirical tool. Even accounting for the possibility of some exaggeration in his statement

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[117] Caspar and Klug, ‘Physical Principles’, p. 3. In this 1962 paper in which Caspar and Klug outline the way in which Fuller’s domes inspired their way out of the virus capsid ‘structural paradox’ and towards the notion of quasi-equivalence, they invoke the term ‘self-assembly’ to describe the virus’s method of construction. This is the first documented usage of the term in this sense. Morgan, ‘Virus Design’.
[118] ‘The World Of Buckminster Fuller’.
[119] Ibid.
[120] Ibid.

that no calculation is needed, this moment – Klug's documented gesture of squeezing and his corresponding reflections on the epistemic function of it – provides a rare glimpse into a scientist's material interaction with a model in the past. It reflects a kind of 'craft knowledge'. 'Craft knowledge' refers to knowledge about and from materials mediated by processes of making, that is, a kind of experimental or empirical knowledge. On one hand, skill, or 'how to' knowledge operates here: how to carve a wooden bowl, cast a lizard in gold, or build a model, for example[121]. This is a sense in which craft has been invoked (loosely) in scholarship on the material culture of twentieth-century science, particularly in relation to technical skills involved in experimentation. But knowledge gained through making may extend beyond that of skill to knowledge of nature or materials themselves. For example, Pamela Smith describes the 'artisanal epistemology' operating among fifteenth and sixteenth century Nuremberg artisans such as Albrecht Dürer, who sought knowledge from and about nature through 'a bodily encounter with matter'[122]. On the topic of three-dimensional models, philosopher of science James Griesemer also stresses physical encounter, urging researchers to 'consider the gestural as well as symbolic knowledge' associated with models[123]; this footage evidences that gestural function in action. As such, this example provides an opportunity to explore the role of materiality in the process of working with models more deeply.

Key to Klug's interaction with the model (on both physical and epistemic levels) are the 'affordances' of the Geodestix. An 'affordance' describes the possibilities of an object or material for an actor. The concept was originally discussed by psychologist James Gibson to describe human interactions with their environment: 'The affordances of the environment are what it offers the animal, what it provides or furnishes, either for good or ill'[124]. For instance, 'the brink of a cliff affords falling off'[125]. After cognitive scientist and design researcher Donald Norman's application of affordance theory to what he called

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[121] Dormer, *The Art of the Maker*.
[122] Smith, *The Body of the Artisan*, p. 59.
[123] James Griesemer, 'Three-Dimensional Models in Philosophical Perspective', p. 435.
[124] James J. Gibson, *The Ecological Approach to Visual Perception* (Hillsdale, New Jersey: Lawrence Erlbaum, 1989 [1979]), p. 127.
[125] Ibid, p. 142

'user-centred design', the concept became embedded in design discourse, particularly in relation to discussions of users' interactions with objects[126]. More recently, anthropologist Tim Ingold has shown the suitability of the concept of affordances for exploring materiality[127]. Noting that anthropologists' discussions of materiality rarely probe actual 'materials and their properties' (paralleling my observation earlier about the histories of scientific models), Ingold advocates 'sensible enquiry into materials, their transformations and affordances'[128]. 'Affordance' speaks to the relational character of physical properties (and is not synonymous with properties themselves), and is thus useful for thinking about the interaction between scientist and model[129].

As Klug shows so clearly on *Horizon*, the thin, hollow plastic rods and connectors that comprise Geodestix afford bending (this is demonstrated in Figure 22). This is significant not only to the 'squeeze' test. The notion that physical material can bend its way out of a perfect geometrical form was actually central to the professional dialogue between Klug and Fuller. It was the key to Klug and Caspar's solution to the 'paradox' of spherical virus structure. As they wrote in 1962, 'there is only one way out of the dilemma. We must drop the insistence on strict mathematical equivalence'[130]. Like Fuller's domes, the virus's protein carapace did not have to conform exactly to a geometric ideal. Rather, the bonds keeping the shell intact, as Caspar and Klug reported, 'may be deformed in slightly different ways' to build the kind of structure that would be consistent with the experimental research of their colleagues[131].

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[126] Donald A. Norman, *The Design of Everyday Things* (New York: Basic Books, 2002, [1988]), p. 187.
[127] Tim Ingold, *Being Alive: Essays on Movement, Knowledge and Description* (Oxon: Routledge, 2011); Tim Ingold, 'Materials Against Materiality', *Archaeological Dialogues* 14 (1) (2007), 1–16.
[128] Ingold, 'Materials Against Materiality', p. 3.
[129] 'It implies the complementarity of the animal and the environment', Gibson writes. Gibson, p. 127.
[130] Caspar and Klug, 'Physical Principles', p. 10.
[131] Ibid.

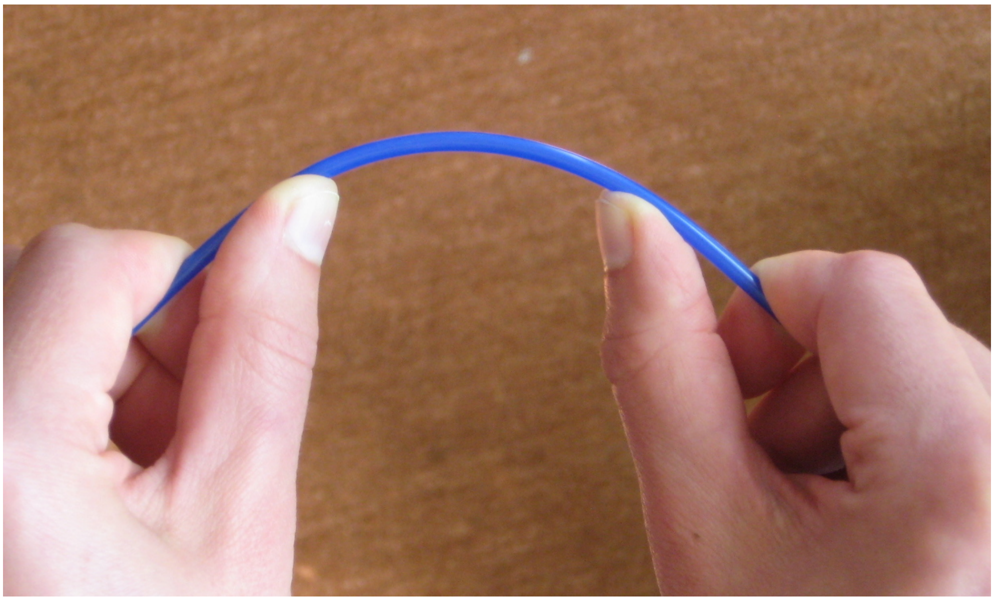

Figure 22 Demonstration of the flexibility of the plastic D-stix straw.

This affordance was crucial to their use of Geodestix. In fact, in using Geodestix to model icosahedral viruses, Klug and Caspar adapted them in a way that departed from their conventional use, bending them out of shape. Caspar wrote, 'the simple, versatile plastic connector with its flexibly joined arm sockets radially arrayed around the orthogonal central hole provides a high degree of built-in adaptability for other construction purposes' beyond those anticipated by Fuller[132]. They were able to build forms in which the 'physical connections between the sticks and sockets' were not 'geometrically equivalent' (as the theory of quasi-equivalence demands): 'The links between the two arm socket domains and the stick domains of each structure unit are stretched and twisted when the units are connected to form a pentamer [an arrangement of five subunits]', Caspar wrote[133]. Image 'c' from the figure included in his article reproduced below shows this twisting (it is somewhat difficult to see in the figure, but some portions of the Geodestix 'net' are 'distorted' in order to create a curved structure)[134]. These are the Geodestix formations Klug was building on *Horizon* (Figure 23).

[132] Caspar, 'Movement and Self-Control in Protein Assemblies', p. 110.
[133] Ibid, p. 112.
[134] Ibid, p. 111.

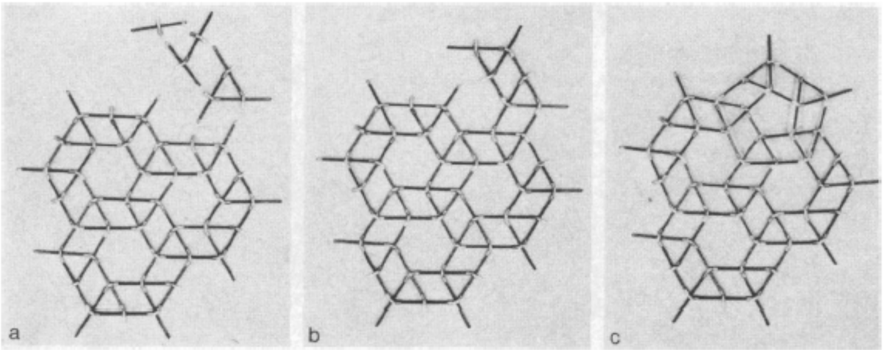

Figure 5 Tensegrity nets. (*a*) Plane hexagonal net with, upper right, a single structure unit (consisting of a stick and two-arm connector), a pair of units connected by a trimer bond, and a trimer. Considering the two ends of the stick and the two arm sockets to be coded the same as the asymmetric unit in Fig. 3, the trimer bonds are between what is defined as the front end of the stick and the right arm socket, and the hexamer bonds are between the back end of the stick and left arm socket. (*b*) The unassembled units in *a* added to the hexagonal net. (*c*) A pentamer has been formed using "hexamer" bonds. The "tension" parts of the structure unit connecting the arm sockets to the sticks have been distorted and the net is now curved. The bonds are still the same as in *a* and *b* but the conformation of the units are now quasi-equivalent.

Figure 23 Figure from Caspar's 1980 paper showing Geodestix formations.

This speaks to an important affordance of the Geodestix, and one I will argue they shared with many other objects and materials used in postwar crystallographic visualisation: they afforded a degree of indeterminacy during the making process. 'This adaptability of the Geodestix connectors is an unplanned, anticipatory feature of Fuller's design that is analogous to the unplanned but purposeful adaptability intrinsic to living structures', wrote Caspar[135]. This comment echoes Fuller's rhetoric of 'anticipatory design', or design that anticipates as-yet-unknown future needs and applications; in addition to adopting Fuller's modelling tools, Caspar and Klug also adopted some of his language – a point discussed further later[136]. More importantly for the discussion of this section, Caspar's comment on the 'adaptability' of Geodestix reflects what he called his 'policy' when model-building: 'underdesign'. This, he writes, 'does not necessarily imply an indeterminate structure, although this is often a

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[135] Caspar adapted D-stix further in an even more flexible 'dynamic' virus model using wooden pegs linked by D-stix connectors. Caspar and Klug, 'Physical Properties', p. 18; Caspar, 'Movement and Self-Control in Protein Assemblies'.

[136] Fuller called his work 'comprehensive anticipatory design science'. Amy C. Edmondson, *A Fuller Explanation: The Synergetic Geometry of R. Buckminster Fuller* (Pueblo, Colorado: Emergent World, 2007), p. 287.

desirable goal'[137]. The desired indeterminacy is easiest to achieve when adapting existing objects from outside the field to modelling, he says, because they were not specifically designed for the purpose of representing the structure at issue. It is only when adapting appropriated components (such as Geodestix) that one learns through modelling. Caspar wrote:

> If all the critical parameters are accurately fixed and the tolerances in construction are high, a model fabricated directly from raw materials [as opposed to those adapted from another purpose] can realize the intended representation but little may be learned in the construction process[138].

Geodestix thus afford risk itself. The indeterminacy that a modelling component or material adapted from another domain brought to the process of scientific modelling corresponds to a particular conceptualisation of craft. Specifically, it echoes the nature of craft practice that woodworker, and design and craft theorist David Pye described as the 'workmanship of risk'[139]. His writing on craft challenged assumptions around craft practice, such as the idea that handcraft was morally superior to machine methods. His 1968 *The Nature and Art of Workmanship*, which introduced the 'workmanship of risk', cut through cultural connotations of craft and skill by focusing on physical processes. This physical emphasis is also what makes it suited to my analysis of the physical interactions between scientists and their visualisation materials.

Pye describes the 'workmanship of risk' as characterised by indeterminacy, a kind of production in which

> the quality of the result is not predetermined, but depends on the judgment, dexterity and care which the maker exercises as he works. The essential idea is that the quality of the result is continually at risk during the process of making[140].

[137] Caspar, 'Movement and Self-Control in Protein Assemblies', p. 110.
[138] Ibid.
[139] David Pye, *The Nature and Art of Workmanship* (Cambridge: Cambridge University Press, 1968).
[140] Ibid, p. 20.

This was essentially his substitute for the word 'crafts' (an attempt to define it in physical, practical terms)[141]. The 'workmanship of risk' is contrasted to the 'workmanship of certainty' in which 'the quality of the result is exactly predetermined before a single salable thing is made'[142]. This describes mass-production methods, and particularly automated mass-production[143]. This does not necessarily mean that craft processes are completely undetermined. Absolutely 'free' workmanship, Pye wrote, patterned by no tool or jig, hardly ever exists, but the emphasis is on craft as a contingent process: the 'workmanship of risk' involves the opportunity for change during a process of making. Similarly, although Geodestix involve inherent constraints, in turning them to a use for which they were not designed, as Caspar pointed out, the researcher injects the process with a degree of indeterminacy.

Several points emerge from this section: it reveals visualisation as a process of making that is, at times, dependent upon the 'workmanship of risk', supported by the affordances of specific materials, and an epistemological acceptance of craft knowledge. Historians of science have noted that materials are often central to the generation of knowledge though modelling; in particular Eric Francoeur argues that knowledge in structural chemistry has in some cases 'hinged [...] upon the working and the sorting out of the geometrical and mechanical properties of physical molecular models'[144]. But evidence of the operation of specific materials or objects is rare, and this is one way in which the example of Klug and Caspar's use of Geodestix is valuable. Examining their use of the toy in a way that focuses on processes and interaction helps make clear the fact that beyond 'properties', the more relational notion of 'affordance' is key to

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[141] Lionel Lambourne, 'Artistic Affinities', in *David Pye: Wood Carver and Turner* (London: The Crafts Council, 1986), ed. by David Pye, pp. 21-24 (p. 21).
[142] Pye, p. 4.
[143] Pye's reflections on 'workmanship' reflect his grappling with the complex relationship between craft and industry from the vantage point of having witnessed the postwar accelerated adoption of mass-production methods in Britain.
[144] He argues, in an article exploring a case study of space-filling models used in biophysics research in the 1930s, that 'steric hindrance ['the way the "volume" of atoms constrains the particular conformation of a given molecule'] is experienced mainly through touch – i.e. one can "see" that a particular structure is hindered because one can feel that specific parts do not fit'. Francoeur, 'Molecular Models and the Articulation of Structural Constraints in Chemistry', p. 95, 100.

understanding models as 'unfolding' things[145]. This material understanding of features of crystallographic visualisation will also make detailed, empirical study of the translation of crystallographic visualisations between scientific practice and design possible later in the thesis.

In addition to providing an evidence-based account of a case in which materiality impinged upon the crystallographic visualisation process, this case demonstrates the value of design history approaches to studying scientific objects. It shows the pertinence of such approaches for studying scientific representation, as this lens provides conceptual tools for understanding material processes at a detailed, tangible level. This case, however, begs further questions about the role risk, materiality and craft knowledge played in the culture of crystallographic visualisation practices more generally. I explore these in the following sections.

Affording risk

Many materials used by postwar crystallographers courted the kind of risk described by Pye in his reflections on craft, and were embedded in processes of generating craft knowledge. In the immediate postwar years this was conditioned in part by the material and economic exigencies facing Britain. Some woods and metals that had been imported before the war were at the time in short supply[146]. Consequently, at the LMB for example, laboratory technician Mike Fuller remembers that in the postwar period, models were made from 'anything you could lay your hands on'. Many of the materials used by LMB scientists came from hobby shops, toy shops, a stationer's and an ex-army radar truck with scrap parts and materials that stopped by once a month 'and everybody could dive in and help themselves to […] anything that was there, and reuse them'[147].

Necessity certainly played a role in crystallographers' use of materials designed for non-scientific purposes. But the case of Geodestix modelling explored above provides insights into further reasons why postwar X-ray

[145] I am quoting Knuuttila's use of the word 'unfolding' from her discussion of approaches to models noted earlier in the chapter. Knuuttila, p. 263.
[146] Edgerton, *Britain's War Machine*.
[147] Interview with Mike Fuller, 19 April 2012.

crystallographers frequently made use of materials from outside the field. Such materials are, like Geodestix, distinguished by their affordance of a degree of indeterminacy precisely *because* they were not designed for modelling molecular structures. The ephemerality, flexibility, reusability and cheapness of many of these materials further afforded the ‘workmanship of risk’ at the research stage.

Plasticine, a brand of modelling clay marketed for children, is a wonderful example. Evidence suggests its heavy use in postwar crystallography modelling especially by the LMB and Cavendish’s crystallographers. Michael Glazer for instance recalled that Helen Megaw of the Cavendish ‘used Plasticine, straws, anything you could get’ for modelling[148]. Mike Fuller recalled that in the 1950s at the LMB, ‘We used Plasticine for everything. I mean now it’s almost impossible to buy, but at the time, Plasticine was the only model-making thing you could get’[149].

Plasticine’s uses included exploring packing arrangements (Bernal used it this way[150]); forming balls in ball-and-spoke modelling (as was dental wax, which was similarly ephemeral and re-usable; it often melted)[151]; and in a documented (and preserved) example, in Kendrew’s ‘sausage model’ of the protein myoglobin, one of the first protein models (Figure 24). Plasticine suited his investigation of folds in a protein’s amino acid chain, and its flexibility

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148 Interview with Michael Glazer, 6 November 2013.
149 Interview with Mike Fuller, 19 April 2012.
150 Bernal explored the close-packing of spheres as part of research on the structure of liquids in the late 1950s using Plasticine. He described the process: ‘Balls of ‘Plasticine’ rolled in chalk were packed together irregularly and pressed into one solid lump. The resulting polyhedra were analysed for arrangement of their polygon faces’. J.D. Bernal, ‘A Geometrical Approach to the Structure of Liquids’, *Nature*, 183 (17 January 1959), 141-147 (p. 143).
151 Michael Glazer recalled Helen Megaw using wax in addition to Plasticine for modelling (interview with Mike Glazer, 6 November 2013). The use of wax in crystallography modelling extends at least as far back as W.H. Bragg. In his 1925 book *Concerning the Nature of Things* Bragg recommended using ‘hard dentists’ wax, which softens in boiling water and can then be pressed into proper shape in metal moulds made for the purpose’. For spokes, Bragg continued, ‘Gramophone needles made good connectors: the balls, wax or wood, being drilled to receive them’. Other mentions of wax balls found in the course of this research are anecdotes concerning their propensity to melt, and thus, their ephemerality: Hodgkin’s group used wax balls in the model-building process of working out the structure of vitamin B12 in the 1950s. Crystallographer Jenny Glusker, Hodgkin’s student at the time who was involved in the research, remembers the balls melting in the heat during the summer as they worked. Physicist Edward Andrade remembered an instance in the early 1920s when W.H. Bragg ‘at an annual dinner of the Alpine Club exhibited a model [of an ice structure], which, being made of soft dental wax, proved itself by wilting as the evening grew warmer’. William Bragg, *Concerning the Nature of Things: Six Lectured Delivered at the Royal Institution* (Mineola, New York: Dover, 2004 [1925]), p. 231; Deirdre Lockwood, ‘100 Years of X-ray Crystallography – Vitamin B12’, *Chemical and Engineering News*, 92 (32) (2014), 38 (p. 38); Edward Andrade, ‘In Memorium: William Henry Bragg’, in *Fifty Years of X-ray Diffraction*, pp. 308-327 (p. 318).

probably afforded the indeterminacy necessary at such an early stage of protein research. The use of Plasticine may have been conditioned in part by materials shortages and the lack of commercial modelling components available in the early postwar period. But that its affordances also represented a key factor in its use by crystallographers is suggested by the fact that even in the late 1950s and early 1960s, when materials shortages had subsided, LMB laboratory records show they were still ordering several pounds of Plasticine a year[152].

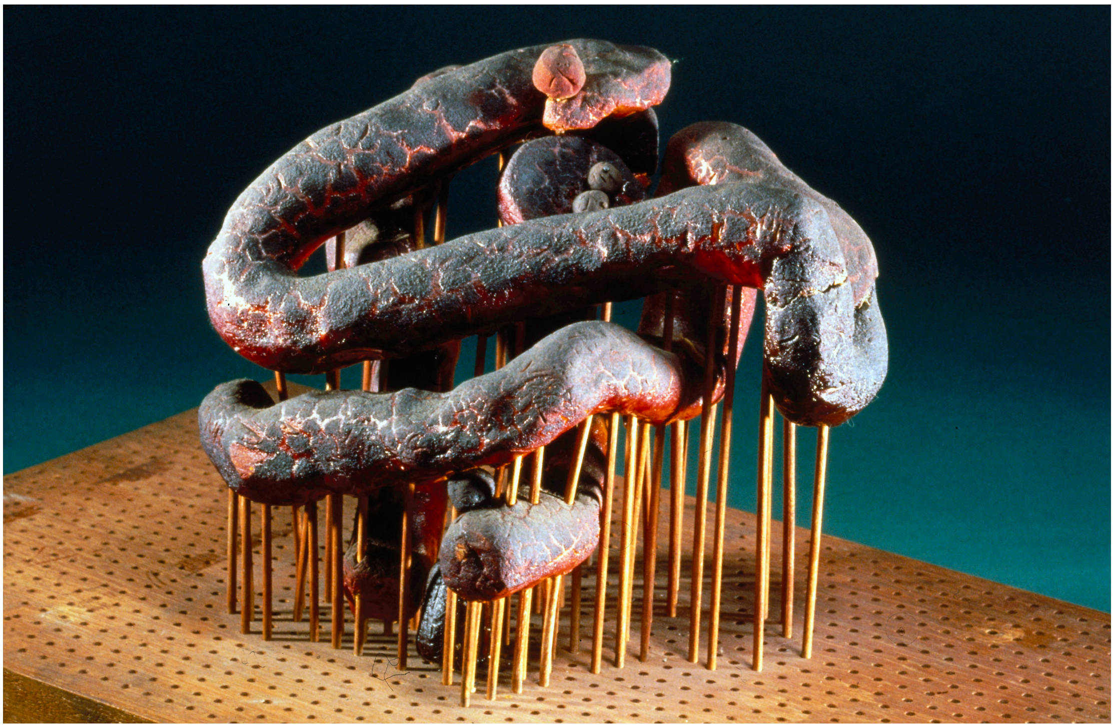

Figure 24 John Kendrew's Plasticine model of a molecule of the protein myoglobin made in 1957.

Several ways in which X-ray crystallographers worked with diagrams in the period also warrant examination as craft processes. Producing and manipulating diagrams could be just as physical and dependent on material affordances and risk as three-dimensional modelling. Recent literature on three-dimensional models calling for greater attention to their materiality largely omits discussion of diagrams, and even defines models in opposition to diagrams as worthy of attention as physical objects, almost as though diagrams were

[152] LMB Laboratory Order Books, 1957-1962. MRC LMB Archive.

immaterial[153]. The affordances of transparent materials such as Perspex and tracing paper, however, were part of the research process, allowing crystallographers to manipulate diagrams in space. For example, electron density maps, mentioned earlier, were printed on Perspex or translucent paper[154]. The transparency and even the flatness of these materials afford a greater spatial understanding of the structure being studied, allowing the researcher to build it up, layer by layer. The fact that Perspex is much lighter than an alternative such as glass (which would have been unwieldy and prone to breakage) also allowed for the layering and manipulation necessary to working with these diagrams. They had to be easily shifted, as matching up features pictured on different maps, their physical layering, and their interpretation were intertwined - engaging head, hand and eye. Dorothy Hodgkin used electron density maps for her wartime penicillin research (Figure 25), and later recalled the process involved:

> the two sheets, you just put together, put one on top of the other and move them one over one another to find which bits hang together, because the arrangement of the molecules are different. […] And then you immediately can see, from the sort of group that fits together and constitutes one molecule, where the phenyl group must be, and where the thiazolidine group must be[155]

As with building models, the scientist receives feedback from the visualisation materials during the process indicating whether she is on the right track, or, when through a process of shifting maps around, areas of electron density come into focus, they 'fit together'. Thus the production of the final arrangement of electron density maps for a given structure depended in part on

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[153] This no doubt has to do with the self-conscious separation from previous literature on 'inscriptions' by scholars writing on three-dimensional models, on the grounds that literature on two-dimensional representation privileged it above three-dimensional models. Francoeur summed up the angle of this research: 'if only by their physical properties, models differ markedly from the "paper" devices traditionally considered in studies of visual representation'. Francoeur, 'Molecular Models and the Articulation of Structural Constraints in Chemistry', p. 96.
[154] When Bragg first piloted the electron density map in 1929, Perspex was not produced yet (it was patented by ICI in 1934). Perspex production increased after the Second World War, and it is probably in the postwar period that Perspex electron density maps became more common. J.P. Tilley, 'Versatility of Acrylics, 1934-1980', in *The Development of Plastics*, ed. by S.T.I. Mossman and P.J.T. Morris (Cambridge: The Royal Society of Chemistry, 1994), pp. 95-104.
[155] Dorothy Hodgkin interviewed by Guy Dodson, 'Work on Penicillin with Charles Bunn', *Web of Stories*, 1990, online video recording. Available at http://www.webofstories.com/play/dorothy.hodgkin/26. Accessed 2 December 2014. Phenyl and thiazolidine are chemical compounds that are part of the penicillin molecule.

those factors Pye located at the heart of making processes involving risk: the 'judgment, dexterity and care which the maker exercises as he works'[156].

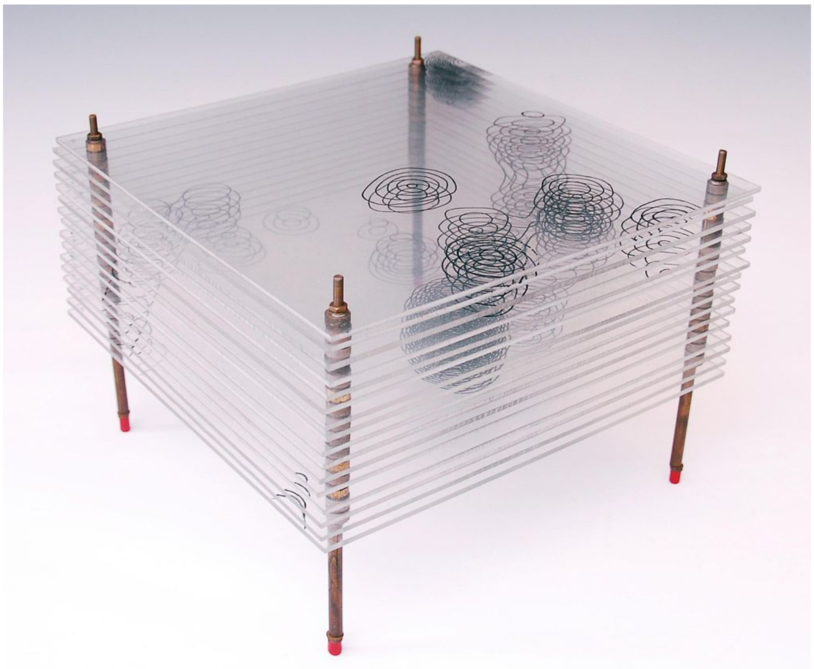

Figure 25 Electron density map associated with penicillin structure research by Dorothy Hodgkin, Barbara Low, C.W. Bunn and A. Turner-Jones (c. 1945).

The use of tracing paper for examining crystal structures in projection also involved processes that operated beyond the site of the two-dimensional page's surface. Shifting and layering were important operations here as well. Glazer recalled the period before the late 1960s (when the use of computers began to dominate visualisation processes), noting, 'I used to use tracing paper, put one thing on top of another, to look for patterns between different projections of a structure'[157]. The research notebooks of Glazer's postdoctoral supervisor and colleague Helen Megaw provide evidence of this material process. They are interspersed with leaves of tracing paper, some of which are scraps, torn at the edges and wrinkled, indicative of their purpose as ephemeral research materials. Many are part of a series of diagrams, with markings indicating that they are to be superimposed on one another. Figures 26 and 27 belong to a series of diagrams picturing polyhedra (formed of oxygen atoms) in a hydroxide structure positioned at slightly different angles of rotation. Available contextual

[156] Pye, p. 4.
[157] Interview with Michael Glazer, 29 May 2015.

information concerning these sketched diagrams is limited so it is difficult to say with certainty exactly what these particular diagrams represent, but they probably compare different orientations of the polyhedra[158].

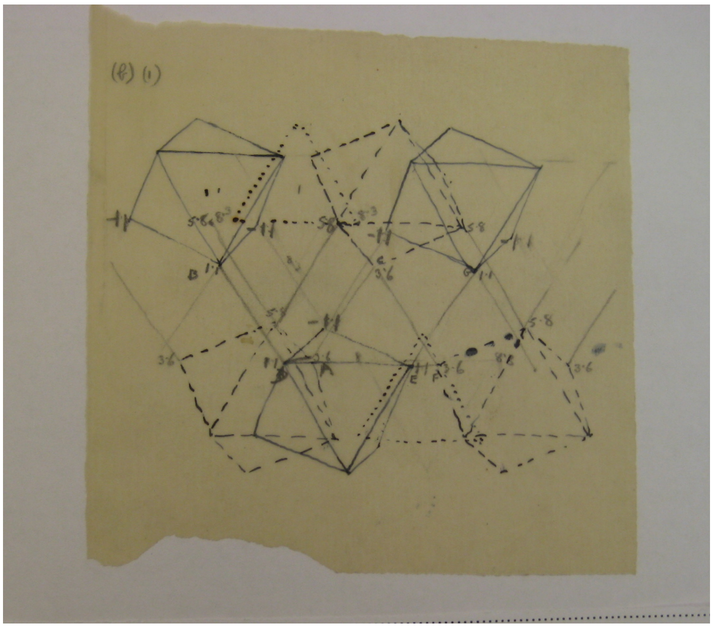

Figure 26 Single leaf of tracing paper '(b) (1)' showing hydroxides tilting diagram from Helen Megaw's laboratory notebooks (possibly c. 1935).

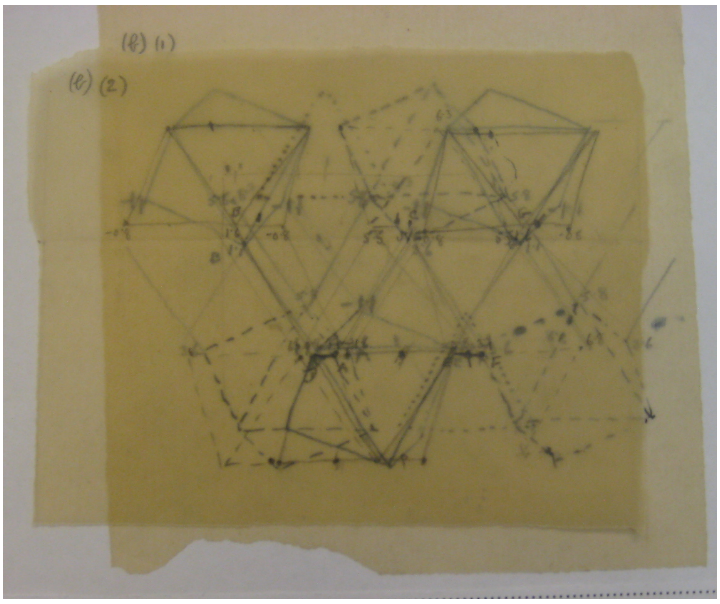

Figure 27 Superimposed diagrams on tracing paper '(b) (1)' and '(b) (2)' showing hydroxides tilting diagram from Helen Megaw's laboratory notebooks (possibly c. 1935).

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[158] Commenting on these diagrams, Glazer said, 'Helen was always looking to see what new crystal structures can be found if you apply some distortions or modifications to a normal crystal structure'. Email correspondence with Michael Glazer, 18 June 2015.

Historians of science have pointed to the manipulation of diagrammatic form on the page as productive of scientific knowledge. Ursula Klein describes formulas, diagrams, and other two-dimensional inscriptions acting as what she calls 'paper tools'. She writes of chemists' 'manipulations of formulas on paper' that allowed them to effectively model chemical processes[159]. In calling them 'tools' Klein makes a claim that diagrams generate data much like any other laboratory tool. More recently Jenny Bangham has pointed to the ways in which twentieth-century geneticists similarly modelled natural processes using systems of nomenclature[160]. The importance of manipulation was equally productive in crystallographic practices of drawing and working with diagrams. But I contend that manipulating the material itself on which diagrams were drawn was just as productive of knowledge as operations undertaken on the page. It was dependent on the affordances of tracing paper and Perspex, and derived from a skilled, dextrous craft process in which the researcher compared and compiled slices or projections of structures and sought patterns across them with eye and hand.

Craft knowledge in the training of crystallographers

This section shows that the craft skills and appreciation of craft knowledge represented in the practices of crystallographic visualisation described so far were transferred tacitly from mentors to students. Traditions of experimental model building in X-ray crystallographic practice began with the Braggs' initial research in the 1910s (likely gleaned in part through their consultation with crystallographers of the pre-X-ray diffraction era)[161]. It is possible to trace a lineage of such practices from the Braggs, through their students, particularly Bernal, and to his students.

A recollection from the crystallographer Reginald James, who collaborated closely with W.L. Bragg after the First World War at Manchester, is revealing. He recalls Bragg emphasising the epistemic value of physical modelling:

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[159] Klein, *Experiments, Models, Paper Tools*, p. 3; Ursula Klein, 'Paper Tools in Experimental Cultures', *Studies in History and Philosophy of Science*, 32 (2) (2001), 265–302.
[160] Jenny Bangham, 'Writing, Printing, Speaking'.
[161] De Chadarevian, 'Models and Molecular Biology'.

> Bragg laid stress on the idea that an atom in a crystal had a characteristic size, and that in deciding on likely structures packing had to be taken into account. He encouraged his pupils to make models, and to see how best the available material would fit into the available space. A structure ought to look sensible, to be so to speak a good engineering job[162].

James' identification of physical models with 'engineering' speaks to the acceptance of practical knowledge gleaned from modelling materials. This indicates the importance of craft knowledge in Bragg's epistemic framework.

This reliance on craft knowledge manifests strongly in W.H. Bragg's student Bernal's practice (who in turn trained numerous crystallographers at Cambridge and later Birkbeck, including Megaw and Hodgkin, who also used visualisation materials in this way). His approach to modelling as a site of physical experimentation is exemplified by his explorations of so-called random close packing, in aid of researching the arrangements of atoms in liquids. Bernal had been interested in the structure of liquids since the 1930s, as he sought a deeper understanding of water in order to advance work on biological substances. One of Bernal's modelling processes for this research involved pouring steel balls into a balloon, followed by paint. 'When the sphere mass was dismantled it was found that each ball had on its surface a series of dots or rings' indicating the site and degree of contact with other balls, which provided information on their arrangement (Figure 28)[163]. Another involved building a ball-and-spoke structure in as random a fashion as he could, using spokes of a variety of lengths based on X-ray diffraction data for liquid metals. He worked in his office where he knew he would be interrupted, as he later explained, 'every five minutes or so' after which he would each time return to work 'not remembering what I had done before the interruption', thus achieving a disordered arrangement (Figure 29)[164]. The original model no longer exists – at

[162] R.W. James, 'Early Work On Crystal Structure At Manchester', in *Fifty Years of X-ray Diffraction*, pp. 420-429 (p. 425).

[163] J.D. Bernal and S.V. King, 'Experimental Studies of a Simple Liquid Model', in *Physics of Simple Liquids*, ed. by H.N.V. Temperly, J.S. Rowlinson and G.S. Rushbrooke (New York: John Wiley and Sons, 1968), pp. 233-252 (p. 238).

[164] J.D. Bernal, 'The Bakerian Lecture, 1962: The Structure of Liquids', *Proceedings of the Royal Society*, A (280) (1964), 299-322 (pp. 301-302). This instance has been recounted by other crystallographers as well as Bernal's biographer Andrew Brown. Brown; John Finney, 'Bernal and the Structure of Water', *Journal of Physics*, 57 (2007), 40–52; Dorothy Hodgkin, *Birkbeck, Science and History. The First Bernal Lecture, Delivered at Birkbeck College, London, 23rd*

least not in a complete form. Bernal did not produce it in a way that was intended to last, using glue to attach rubber balls to rods, rather than the more secure conventional method of drilling holes in the balls. He built the model as a process of gaining knowledge about a structure, an objective he could not achieve without carrying out its material production, and seeing how the structure unfolded. Maintaining some uncertainty about its final form during the process of making - the marker of the 'workmanship of risk' - was an explicit goal in the production of this model.

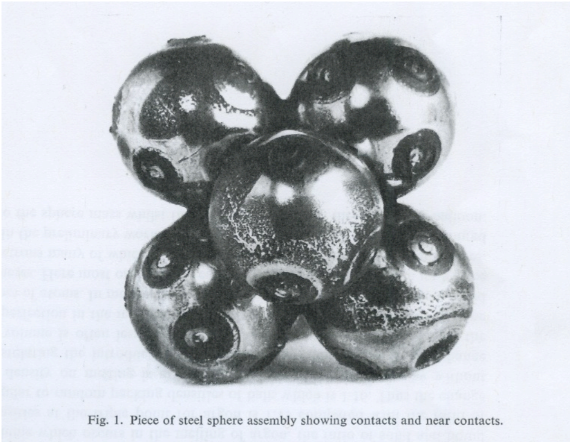

Figure 28 Steel balls covered in paint from Bernal's packing experiment.

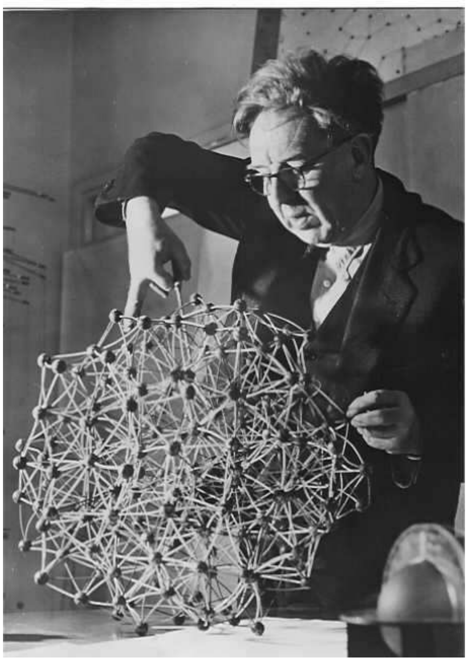

Figure 29 Bernal building a model of a liquid structure in his office in an undated photograph from collection of his colleague John Finney (probably c. 1959).

October 1969 (London: Birkbeck College, 1970). Bernal also published on this research in Bernal, 'A Geometrical Approach to the Structure of Liquids'.

Glazer trained in the 1960s, just before physical models and diagrams gave way to computerised visualisation methods. He employed the empirical modelling methods of his mentors. For example, he described building a packing model out of cork in the 1960s that echoed the methods of the Braggs:

> There was nothing available easily at the time […] So I had to actually buy lots of corks and cut them up myself. Very much in the way that Bragg did in the 1930s[165].

When asked how such material experimentation was instilled in his working methods, Glazer's response revealed the difficulties involved in tracing the transmission of such craft practices:

> I don't think I was ever trained as such. So many things you just sort of…Models were around. You could see what they were. You pick it up as you go along[166].

Like many craft practices, visualisation methods were passed down informally in the laboratory or workshop environment and practitioners cannot always explain or pinpoint how they learned. This corresponds to the tacit qualities of knowledge transfer authors evoking craft knowledge from both design and science scholarship identify[167]. Steven Shapin and Simon Schaffer, for example, write that no one could replicate seventeenth-century scientist Robert Boyle's air pump without 'visual experience' of the instrument's trials; 'no one relied on Boyle's textual description alone'[168]. The transmission of these skills, was, in practice, tacit, as Glazer indicated ('You pick it up as you go along')[169]. This speaks to the lack of formalised training in visualisation practices in the period, discussed later.

In sum, this section demonstrates the role of the 'workmanship of risk' and craft knowledge in postwar crystallographic visualisation practice beyond the

[165] Interview with Michael Glazer, 29 May 2015.
[166] Ibid.
[167] Sennett; Dormer, *The Art of the Maker*; Shapin and Schaffer.
[168] Shapin and Schaffer, pp. 229-230.
[169] Interview with Michael Glazer, 29 May 2015.

Klug-Caspar collaboration. This feature of the crystallographic practices highlighted here was socially contingent, transmitted through the training of crystallographers in a tradition linked to the Braggs. As the next section makes clear, this means it did not manifest in the working styles of all crystallographers in the same way.

Border crossings

This section demonstrates how the case of Klug and Caspar's virus modelling reveals the challenges of imposing clear boundaries around what constituted the culture of visualisation practice operating in postwar X-ray crystallography. This case points to the ramifications, for describing postwar crystallographic practices, of the fact that at this time, crystallographic training was relatively unfixed and practitioners joined the field from myriad disciplinary backgrounds. It also prompts reflections on the cross-disciplinary exchange underpinning Klug and Caspar's use of Geodestix.

Klug's demonstration of an acceptance of craft knowledge on *Horizon*, noted earlier, may actually point to his own surprise at its role in the virus research. This is because, as Klug explains on the programme, he was not predisposed to approach the problem of icosahedral virus structure in this way given his training and disciplinary background. During his conversation with Fuller on *Horizon*, Klug discusses the relationships between material empiricism and abstract knowledge in his research, and the ways in which his encounter with Fuller's approach to materiality affected his thinking. Klug emphasises the dichotomy between the geometrical ideals he originally sought in virus structure (the notion of strict icosahedral symmetry) and his development of material understandings, which helped him to drop geometrical ideals for the concept of quasi-equivalence. The effect of Fuller's objects, expressed in Klug and Caspar's 1962 article and on *Horizon*, is that the abstract Platonic ideal subsides. It is literally bent out of its shape, as the affordances of material objects - the geodesic dome's struts and bendable Geodestix - intervene[170]. Reflecting before the

[170] Klug and Caspar describe the demotion of the geometrical ideal in their paper, writing, 'Molecular structures are not built to conform to exact mathematical concepts'. Caspar and Klug, 'Physical Principles', p. 10.

Horizon cameras, Klug recalled that he had previously ‘always thought of an icosahedron as this perfect, you know in the Greek sense, a perfect object’[171]. But such an approach presented a ‘stumbling block’ when it came to understanding virus structure: ‘We always wanted to make the Greek ideal and never the real thing’, he said[172]. By contrast, Klug casts Fuller as a bearer of craft knowledge. Addressing Fuller, Klug remarked, ‘When you see an edge, you actually see it as made of real rods and struts and things […] one of the things I’ve learned from the way you make your things is that you abandon traditional classical mathematics when you’re discussing making real objects’[173]. Fuller’s style of working was dependent on physical modelling and he exhibited a stubborn insistence on thinking in material terms, often claiming, contrary to an axiom of Euclidean geometry, that two lines *cannot* go through a single point (which he ‘demonstrated’ on *Horizon* by crossing two rods in the air).

After describing the demotion of geometrical ideals in his virus research, Klug says, referring to paper geometrical models of icosahedra before them, ‘this is a useful starting point’, but, ‘well you learn to forget’. Klug’s paper models of icosahedra are geometrical models, representing ideals (Figure 30). These may have been part of his working process in earlier stages of the research in which he assumed the virus structure to conform to strict icosahedral symmetry. What Klug learned to ‘forget’ is the approach to virus structure as a geometrical problem. He says ‘forgetting’ about ‘traditional classical mathematics’ was ‘in my own work […] the hardest step’[174].

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[171] ‘The World of Buckminster Fuller’.
[172] Ibid.
[173] Ibid.
[174] Ibid.

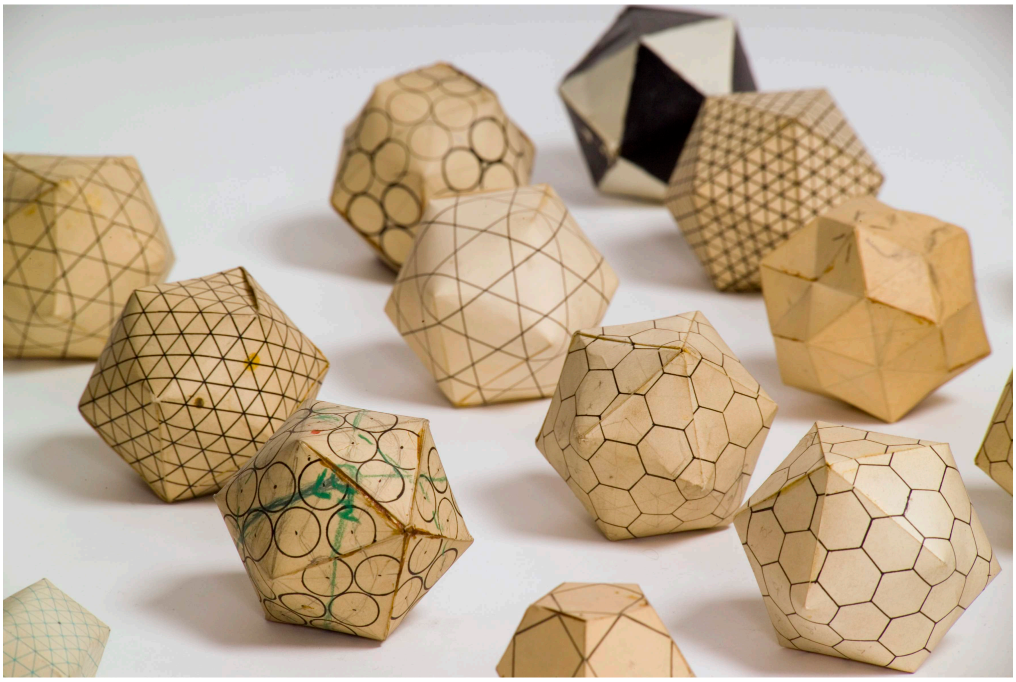

Figure 30 Aaron Klug's virus/geometric models exploring possible virus structure.

On one hand, Klug's emphasis on the encounter between his propensity for abstract thinking and Fuller's material empirical methods reflects the fact that this case is an example of the role of materiality and craft knowledge in the development of theory (much of this research on virus structure pertaining to quasi-equivalence was theoretical work). On the other, it speaks to Klug's disciplinary background in mathematical physics, the field in which he had completed his doctorate. Klug's training positions him just outside the direct lineage from the Braggs pointed out earlier, through which an emphasis on craft knowledge was passed down. Klug had completed his doctorate in physics at the Cavendish under the mathematical physicist Douglas Hartree on the cooling of steel[175]. Klug referred to this aspect of his background on *Horizon* when discussing his initial approach to the virus structure problem as an abstract geometrical problem, explaining, 'I'm a physicist by training'[176].

This demonstrates that it is not enough to simply claim that material

[175] Klug had learned X-ray crystallography techniques during his MSc at the University of Cape Town under Reginald James, formerly of Bragg's Manchester crystallography group, but did not undertake a PhD in the field. He had wanted to pursue a doctorate at the LMB on the X-ray crystallography of proteins, but was told the laboratory was full, so studied with Hartree instead. Klug's move to Birkbeck in 1953 following the completion of his doctorate, he remembers, offered him 'an opportunity to get back into crystallography'. Aaron Klug interviewed by Tony Crowther and John Finch; Finch, *A Nobel Fellow on Every Floor*.
[176] 'The World Of Buckminster Fuller'.

models were heuristic tools in X-ray crystallography research of the period. Within a general epistemic framework in which scientists exhibited trust in what I have described here as craft knowledge, this manifested in different ways, to varying extents, and was subject to individual styles of working and disciplinary backgrounds. This was conditioned by the fact that many postwar X-ray crystallographers emanated from different disciplines, as Klug's biography attests. Furthermore, crystallography training was hardly formalised by the 1950s. Only a few dedicated crystallography degree courses existed. This led Lonsdale (the head of one of those departments with a crystallography degree at UCL) to complain in 1953, 'it is still difficult for a thorough training in the subject to be obtained' resulting, in her view, in many ill-prepared young researchers[177]. The inconsistency in the training of crystallographers may have contributed to the potential variety within postwar crystallographic visualisation practice demonstrated by Klug's case.

The case of virus modelling explored here also demonstrates the difficulty of delineating strict national boundaries around cultures of practice, due to Caspar's role in the story. Indeed Klug's use of Geodestix was conditioned not only by his exchange with Fuller, but by his transatlantic collaboration with Caspar, who, as mentioned earlier, brought the construction toy into their research process. Caspar's own training and postwar collaborations link his practice to British centres of X-ray crystallography even though he was trained and worked primarily in the US. Not only was he in frequent contact and collaboration with Birkbeck and Cambridge crystallographers, but Caspar had also learned X-ray crystallography from Isidor Fankuchen, a former post-doctoral researcher under W.L. Bragg and Bernal[178]. Caspar's role in the case explored here reflects the fact that British virus crystallographers were part of a larger international community of molecular biology research[179].

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[177] Lonsdale, 'The Training of Modern Crystallographers', p. 875.

[178] Fankuchen and Bernal's prewar collaboration initiated X-ray crystallographic research into viruses. Creager and Morgan, 'After the Double Helix'.

[179] Creager and Morgan, 'After the Double Helix'; de Chadarevian, *Designs for Life*; Pnina Abir-Am, 'From Multidisciplinary Collaboration to Transnational Objectivity: International Spaces as Constitutive of Molecular Biology, 1930–1970', in *Denationalizing Science: The Contexts of International Scientific Practice*, ed. by Elisabeth Crawford, Terry Shinn and Sverker Sörlin (Dordrecht: Kluwer, 1992), pp. 153–186.

This case also speaks to the sense in which the modelling tools and conventions aligned with X-ray crystallography were rarely limited in their use to this field alone. Geodestix became part of the culture of crystallography after Klug and Caspar's initial use of them[180]. But they also took on a life in virus modelling outside X-ray crystallography practice. As tools useful for the theoretical exploration of possible structures, Klug also continued using Geodestix after 1962 during which time he used electron microscopy as the primary experimental method for the very structural research into viruses that he began when he used X-ray crystallography techniques[181].

Finally, the case of Klug and Caspar's interaction with Fuller makes an important point about the flows between postwar X-ray crystallography and design fields. The exchange of knowledge between cultures (whether in the form of text, pattern, or a visualisation tool as in this case) is rarely reciprocal[182]. In this example, it was Klug and Caspar's work that was more greatly affected by the interaction with Fuller, rather than the other way around (although Fuller received publicity as a result, as the *Horizo*n episode attests). Whereas most historiography on the subject of X-ray crystallography's interaction with design highlights a unilateral trajectory of science's influence on design (as noted in the thesis introduction), this case provides evidence of the flow of knowledge, practices and objects in the other direction. Just as X-ray crystallographers adapted visualisation tools and components from other scientific fields, in this case, Klug and Caspar adapted a tool, Geodestix, which they encountered through its use in the context of architecture. In addition to movement of material

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[180] Sets were included in at least one catalogue from the 1960s of the firm Crystal Structures Ltd, which supplied models and modelling components to crystallographers throughout the country, and they are included in chemist Ann Walton's 1978 survey of then-current crystal and molecular structure modelling techniques. Crystal Structures Ltd catalogue, c. 1960s, Crystal Structures Ltd Archive; Ann Walton, *Molecular and Crystal Structure Models* (Chichester: Ellis Horwood, 1978).

[181] A. Klug and J.T. Finch, 'Structure of Viruses of the Papilloma-Polyoma Type', *Journal of Molecular Biology*, 11 (February 1965), 403-423; J.T. Finch and A. Klug, 'The Structure of Viruses of the Papilloma-Polyoma Type 3. Structure of Rabbit Papilloma Virus, With an Appendix on the Topography of Contrast in Negative-Staining for Electron-Microscopy', *Journal of Molecular Biology*, 13 (August 1965), 1-12.

[182] Scholarship from the transnational history of science is instructive here: historian of science John Krige's research on Anglo-American cooperation on equipment for uranium enrichment in the 1960s reminds historians 'that knowledge often flows in an asymmetric' manner, affected by power differentials and other factors disrupting perfect 'reciprocity' of exchange within a network. John Krige, 'Hybrid Knowledge: The Transnational Co-Production of the Gas Centrifuge for Uranium Enrichment in the 1960s', *British Journal for the History of Science*, 45 (3) (September 2012), 337–357 (p. 340).

objects from design to science, concepts and terminology associated with Fuller also surfaced in the scientists' conceptualisations of virus structure. These are worth noting briefly as they further indicate Fuller's effect on the scientists' thinking. In their 1962 paper Caspar and Klug describe their search for 'efficient designs' of the virus shell, echoing Fuller's devotion to developing efficient designs for human needs such as housing[183]. Furthermore, Klug's emphasis on *Horizon* on the dichotomy between geometrical 'Greek ideals' and material realities (quoted earlier) clearly corresponds to ideas he expressed in later interviews on this topic, but it is significant that he expressed these ideas on *Horizon* through framing and language that echoed Fuller's outlook. The stark dichotomy between Platonic form and 'real object' parallels Fuller's own self-conscious distinction between his own material approach and much continental modernist rhetoric, which lauded geometrical ideals[184]. This case reveals the crystallographic visualisation as a rich site of cultural exchange – an idea pursued further in chapter two.

Conclusion

This chapter's analysis of X-ray crystallographic visualisation as a craft process presents new empirical examples of the role of materiality in postwar X-ray crystallographic visualisation. It also advances a cross-disciplinary methodology (and a new source, in the form of BBC science television) for examining the scientific objects under discussion. In doing so, it interrogates the materiality of the visualisation process more deeply than previous scholarship on X-ray crystallography models and diagrams. It also complicates the picture of postwar British crystallography, for the case study explored is, as mentioned earlier, representative precisely because it appears in many ways to be unrepresentative of postwar X-ray crystallography research. That is, the researchers involved did not use solely X-ray crystallography methods, their models did not result from

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[183] Caspar and Klug, 'Physical Principles', p. 1.

[184] Fuller defined himself against architects of the continental modern movement, but he was also in a sense a student of their work. Fuller had studied the work of modernist architects Le Corbusier and Walter Gropius in the late 1920s, and the notion of Platonic form structured Fuller's thinking and practice (even if his material structures departed from strict geometric ideals). On Fuller's study of modernist architects see Gorman.

'direct' interpretation of X-ray crystallography data, they drew upon an unusual source in their modelling approach and components (Buckminster Fuller), and the case cannot be described as an instance of work by British scientists alone. As I argued throughout, a thorough accounting of postwar X-ray crystallography must acknowledge these aspects of crystallography practice in postwar Britain.

Furthermore, Klug's reflections on his virus research provide a way in to exploring a key aspect of the contingencies shaping the role of craft knowledge in postwar crystallography: training (a topic in the history of postwar X-ray crystallography that has seen little research). Methods of visualising structures represent craft skills and an appreciation of craft knowledge transferred tacitly from mentors to students. But not all crystallographers active in postwar Britain were trained in crystallography departments where such tacit transfer might occur. As a young field – and one that overlapped with so many others – training in X-ray crystallography was not highly formalised at this time. This meant, as a frustrated Lonsdale contended in 1953, that many crystallographers began their careers without all the skills an X-ray crystallographer might need[185]. It also contributed to variety in visualisation practices and perhaps to the fluidity of forms and materials used in these practices as well.

Bruno Latour describes scientific representations as 'immutable mobiles', maintaining they are useful partly because of their 'optical consistency' or 'immutability' (an idea echoed in Eric Francoeur's recent research on molecular models)[186]. This chapter's analysis of postwar crystallographic visualisation highlights a different feature: the mutability of their form and materiality. This mutability is found at the level of an individual research project in which the 'workmanship of risk' operates. It is also evident more broadly, in the adaptation of new materials and methods, as in Klug and Caspar's *bending* of Geodestix to suit their needs during the course of their research. This corresponds to recent research by historian David Kaiser who traces the postwar use of Feynman diagrams across communities of physicists[187]. Kaiser discovered that as they

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[185] Lonsdale, 'The Training of Modern Crystallographers'.
[186] Bruno Latour, 'Drawing Things Together', in *Representation in Scientific Practice*, pp. 19-69 (pp. 27, 32); Francoeur, 'Molecular Models and the Articulation of Structural Constraints in Chemistry'.
[187] Feynman diagrams, used in physics since the 1940s, outline interactions between electrons and other subatomic particles.

spread internationally they were 'constantly refashioned', deployed differently according to local conditions, such as modes of training and research emphases[188]. Their repeated transmission shows how 'plastic' the diagrams were; their actual form was subject to 'tweaking'[189].

The notion of examining the materiality and contingent nature of X-ray crystallographer's visualisations is not a revolutionary proposition from the perspectives of either histories of science or design. But X-ray crystallographic visualisation practice had not been explored in an in-depth and dedicated way from such a perspective. This chapter contributes to the history of X-ray crystallography in part through its aim to address this gap. That being said, my approach is not that of a sociologist of science, and also differs from existing research by historians of science on representations (which was an aim, as this chapter pilots the approach of craft scholarship to such subjects). Larger social conditions pertaining to training frame my analysis of contingencies at a more tangible scale: the level of *risky* material interactions consisting in hands bending plastic D-stix, shifting diagrams inscribed on tracing paper, and gluing rods (precariously) to rubber balls.

The above conclusions of this chapter are primarily about scientific practices and objects, typically the subject matter of scholarship about science. But topic is only one way to define a discipline. Fields are also characterised by their methodologies and the kinds of questions researchers ask. It is in these areas that this chapter advances arguments for design history. This chapter demonstrates that design history methods, through perspectives from craft scholarship and attention to production practices and materiality, possess utility beyond conventional subjects of design history. The questions outlined earlier that design and craft scholars ask about craft practices can advance understanding about scientific practices – questions about the status of craft knowledge, specific materialities, and processes of making that understand

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[188] Kaiser, pp. 9, 6. The title of Kaiser's book, *Drawing Theories Apart*, references Latour's 1986 essay on scientific inscription, 'Drawing Things Together' and signals Kaiser's critique of Latour's thesis concerning the necessity of inscriptions to be 'immutable mobiles'. Kaiser focuses instead on the 'unfolding variations within [physicists'] work - on the production and magnification of local differences, and the work required to transcend these differences when comparing results from different places' (p. 7).

[189] Kaiser, p. 174.

objects, as Adamson put it, 'in motion'[190].

Recent scholarship on design and craft has broadened out from a connoisseurial product-focus to include investigations of practices. In so doing, design history discourse aligns with concerns of sociologists and historians of science who have been asking questions about social practice for decades. Design historians' focus on practices generates the potential for design historical study of practices of production beyond those of design or craft as they are conventionally construed. This chapter's methodological cross-fertilisation thus seems like a logical, almost obvious, step given the recent directions of both histories of design and science. It is, however, one that had not been pursued.

Working in the overlap between the methodologies and concerns of the histories of science and design aids the study of interactions between fields. Scientific objects do not operate only in the laboratory, of course; they enter contexts that bring them into the view of scholars in other disciplines, including design history, as the next chapter's case, the Festival Pattern Group, demonstrates. Boundaries around disciplines need to be flexible enough to account for the movements of things.

A historically contingent understanding of crystallographic visualisation has not informed existing historical accounts of the science-inflected designed objects studied later in this thesis. In this sense, this chapter's analyses will also contribute to subsequent discussions. In chapter two, the understanding of crystallographic visualisation as a craft process will inform my analysis of encounters between crystallographic visualisation and design practice in the context of the Festival Pattern Group. It will take the notion of the crystallographic visualisation's mutability further, seeing the visualisation circulate and undergo manipulations outside the bounds of scientific research practice.

[190] Adamson, *Thinking Through Craft*, p. 4.

Chapter Two

Decorative Diagrams:
Reassessing the Cultural Transmission between X-ray Crystallography and Industrial Design in the Festival Pattern Group Project

Introduction

This chapter advances a new narrative of the Festival Pattern Group (FPG), a project for the 1951 Festival of Britain in which crystallographic diagrams formed the aesthetic basis for pattern design. It employs history of design and science perspectives to analyse the transmission of crystallographic diagrams from science to industrial design for the project. This results in an account that goes beyond existing ones: it reveals that the cultural transmission at the heart of the FPG emerged from a complex, discipline boundary-crossing constellation of figures from cultures of science, fine art, architecture and design, who were embedded in varied aesthetic frameworks, ideologies and practices and guided by different interests. This revised reading of the FPG challenges the contextual and disciplinary frames used to examine the topic previously. It also yields insights regarding the postwar history of X-ray crystallography in a culture outside of scientific research: modernist design networks.

Formed under the aegis of the Council of Industrial Design (CoID) and orchestrated by its Chief Industrial Officer Mark Hartland Thomas, the FPG brought together 28 British manufacturers to produce objects bearing patterns based on crystallographic diagrams, which were exhibited at the 1951 Festival. Constituent manufacturers included producers of textiles, wallpapers, wrapping paper, ceramics, and furniture, and goods in glass, metal, rubber, and plastics. X-ray crystallographer Helen Megaw of the Cavendish Laboratory was the FPG's scientific adviser. She selected and drew crystal structure diagrams for the group, dyeline prints of which were circulated among the manufacturers' designers. The FPG also included designers Misha Black and Alexander Gibson, who were responsible for the interior of the Festival's Regatta Restaurant (the primary location where the FPG's products were displayed). Over 80 designs resulted from the project, including wallpaper printed with a pattern based on the structure of nylon and lace woven according to the structure of the mineral apophyllite.

The FPG was an unusual instance of an organised scheme in which crystallographic visualisations were deliberately used as an aesthetic reference point in the design of domestic objects. It is a valuable case study of the use of science-inflected ornament in objects of postwar British industrial design precisely because it represents such an unusually close (and well-documented) instance of exchange between fields[1]. This means that the FPG provides an opportunity for detailed examination of the mechanisms of a cultural transmission from science to industrial design. Additionally, because of these factors the FPG has been researched more than any other topic pertaining to science-inflected ornament or cross-field relationships between science and industrial design[2]. This makes it a productive subject for the historiographical and methodological investigations of this thesis, as this chapter identifies problems with the existing historiography and exhibits an alternative approach to the FPG.

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[1] Both the CoID, which retained records of meetings and correspondence associated with the FPG, and Helen Megaw have left behind sizable archives pertaining to the group's work. Details on archives are provided in the 'Methodology and sources' section of this chapter.

[2] Texts on the FPG include Jackson, *From Atoms to Patterns*; Lesley Jackson, 'The Appliance of Science', *Crafts*, 211 (2008), 32-35; Tom McGill, 'Design Under the Microscope: The Festival Pattern Group 1951: The Council of Industrial Design and the Mechanics of Industrial Liaison', *The Decorative Arts Society Journal*, 31 (2007), 92-115; Mary Schoeser, 'The Appliance of Science', *Twentieth Century Architecture 5: Festival of Britain*, ed. by Elain Harwood, Alan Powers (London: Twentieth Century Society, 2001), pp. 118-126; Lesley Jackson, 'X-ray Visions', *Crafts*, 172 (2001), 32-35; Forgan, 'Festivals of Science'. The FPG is also mentioned, usually quite briefly, in many surveys of postwar British design and texts on the Festival of Britain including Harriet Atkinson, *The Festival of Britain: A Land and Its People* (London: I.B. Tauris, 2012); *British Textiles: 1700 to the Present*, ed. by Linda Parry (London: V&A, 2010); Lesley Jackson, *Twentieth Century Pattern Design* (New York: Princeton Architectural Press, 2002); Becky E. Conekin, '*The Autobiography of a Nation': The 1951 Festival of Britain* (Manchester: Manchester University Press, 2003); Becky Conekin, 'Here is the Modern World Itself': The Festival of Britain's Representations of the Future', in *Moments of Modernity: Reconstructing Britain, 1945-1964*, ed. by Becky Conekin, Frank Mort, Chris Waters (London: Rivers Oram Press, 1999), pp. 228-246; Jackson, *The New Look*; Lesley Jackson, *Contemporary: Architecture and Interiors of the 1950s* (London: Phaidon, 1994); Woodham, *Twentieth-Century Ornament*. A product of the fact that this chapter represents a reassessment of existing narratives of the FPG is that some of the events, figures and features of the project covered here are also mentioned by other authors, and many of the diagrams included for analysis have been published as FPG source material by other authors, but not in the same interpretive context as they are here (most frequently they have been given outside of an interpretive context). In this chapter, these diagrams, events and figures appear within a new narrative of the project alongside much new archival research and contextualising information not previously considered in histories of the FPG.

Cultural transmission is a key concept in this chapter. As mentioned in this thesis's introduction, this concept refers to the movement and translation of things such as knowledge, objects, or practices between cultures (by way of communication through social networks or media, or through the circulation of objects, for instance). In this case, the cultures in question are the professional spheres of crystallography and industrial design.

My focus is primarily on the transmission and translation of crystallographic diagrams between crystallography and design in the germination and early stages of the FPG project and process[3]. I argue that cultural transmission in these stages was crucial to the project's overall aesthetic mission of generating pattern designs based on crystallographic visualisations. I investigate how crystallographic diagrams reached figures in industrial design in the context of the FPG, why particular people from this culture were interested in them (not everyone was), how practitioners in fields outside of crystallography received them, and how the diagrams were mediated during this process of transmission. The focus on mechanisms of cultural transmission brings up questions that are so far under-researched in the context of the FPG: questions about the direction of flows between cultures of design and science (which were, I argue, multidirectional), and about the specific factors conditioning the exchange between design and crystallography that ignited and characterised the FPG project. The result is a more nuanced understanding of cultural transmission between science and design than that assumed by most postwar British design history considering science-inflected ornament.

This chapter presents new angles on the story of the FPG. The topic has seen archival research, which this study builds upon, by design historians Lesley

[3] This chapter is therefore not a comprehensive account of the FPG story. The scope of this chapter does not extend to an analysis of the final pattern designs produced or exploration of the work of FPG designers. In addition to the fact that consideration of the final designs is somewhat beyond the focus of this chapter's question, practical considerations of space and sources precluded extension of the scope of this chapter to include analysis of the designs and the work of the group's designers. Such an analysis would require much more space as the work of FPG designers, which is not well-documented as a whole (with material scattered across numerous manufacturers' archives if at all), presents challenges in terms of developing a comprehensive picture given the number of industries and manufacturers involved. For an account of the FPG's formation, administration, the designs produced, reception and life after the 1951 Festival, see Jackson, *From Atoms to Patterns*.

Jackson and Tom McGill and the historian of science Sophie Forgan[4]. Much literature on the topic is weighted toward description however, leaving much room for interpretation of the FPG. Furthermore, literature on the FPG emanates primarily from design history perspectives apart from Forgan's brief suggestive analysis from the angle of the public display of science at the 1951 Festival[5]. This is reflected in the historiography's focus on the FPG's resultant designs, and conceptualisation of the project in terms of Festival and CoID aims[6].

Existing narratives of the FPG picture the transmission of crystallographic visualisation from science to design in the project as a unidirectional trajectory, and assume the professional design contingent was where the responsibility for the real aesthetic work of the project's cultural translation rested. This is made evident by the fact that the question of cultural transmission is principally explored through discussions of the final pattern designs: authors discuss the degree to which they resemble their source diagrams (which most point out was very closely), and the positions of various FPG members on how much they should[7]. The result of many accounts of the FPG is that the crystallographic diagram appears as the impregnable authentic source that designers then translated, as an immutable thing[8].

[4] Jackson, *From Atoms to Patterns*; Wellcome Collection, London, 'From Atoms to Patterns' (24 April-10 August 2008); McGill; Forgan, 'Festivals of Science'.
[5] Forgan, 'Festivals of Science'.
[6] McGill; Schoeser. The historical frame of the Festival (including its science remit and/or the role of CoID goals for industrial design) dominates the literature on the FPG enumerated in the footnote above listing sources on the topic, including Forgan's article on the FPG from the perspective of the history of science (Forgan, 'Festivals of Science').
[7] Jackson writes, 'Although some manufacturers' interpretations were freer than others, what is remarkable is how respectfully the source material was treated'. Discussions of the FPG's final patterns' visual resemblance to source diagrams are sometimes inflected by the authors' own judgments of the designs produced by the FPG. For example, McGill writes, 'Those designers whose translation was literal were sometimes the least aesthetically successful'. Mary Schoeser also focuses on whether or not given patterns conformed to their source diagrams. She writes that 'departure' from the diagrams is 'most evident in dress fabrics', claiming that this is because the textile industry 'has to follow fashion, it can't be pinned down and therefore many designers weren't having these rigid crystal patterns at all'. Forgan also presents the FPG project as comprised by contentious unidirectional transmission between cultures espousing two opposing approaches: that of scientific accuracy, and a vision of design in which she speculates that 'artists and designers expected to have complete freedom in using the patterns for inspiration or source material in whatever way might be most appropriate for the product in question'. Jackson, *From Atoms to Patterns*, p. 29; McGill, p. 105; Schoeser, p. 122; Forgan, 'Festivals of Science', p. 225.
[8] The only source on the FPG that attends to the scientific diagram itself as a more mutable object, through description of aspects of its construction, is the analysis by the historian of science, Forgan ('Festivals of Science'). Yet this article also sees the work of translating the diagram to design as the responsibility of the designers, and imagines the diagram, and

Approaching the FPG with the perspective on crystallographic visualisation developed in chapter one leads to a different angle on the project. As chapter one emphasised, practices of crystallographic visualisation were already, like the culture of postwar X-ray crystallography itself, part of a continual process of hybridisation in which the tools and questions of many scientific fields interacted, and which were conditioned by frameworks of scientific practice and individual scientists' training. These are fundamental conditions of any scientific product or activity, but they are not taken into account when design histories invoke the influence of 'science' as a monolithic entity.

The notion of the contingent nature of crystallographic visualisation practice underpins this chapter's identification and analysis of a key site of the project's transmission of diagrams from science to design that existing histories have not interpreted as such: Megaw's production of diagrams for the group. This chapter shows that Megaw's work for the group was a crucial yet unacknowledged site of translation of crystallographic diagrams from the scientist's 'paper tool' to pattern design in the FPG. I argue that the diagrams Megaw submitted to the FPG exhibit both conventions of postwar crystallographic diagrams and conventions of design drawing. Specifically, I contend that they are inflected by conventions associated with a specific mode of ornamental composition: those of the so-called 'South Kensington system' of design education, taught in Britain from the mid-nineteenth century through the early twentieth century (the South Kensington system is described further later in the chapter). I show that Megaw's early design education, which was shaped by the South Kensington method of design drawing, affected her FPG work. Neither the South Kensington style of design drawing, the presence of design conventions in Megaw's diagrams, nor Megaw's own design education have been subjects brought up in previous accounts of the FPG. Megaw's deployment of design conventions in her production of diagrams for the FPG problematises aspects of the existing narrative of the FPG: this analysis challenges the model of a unidirectional trajectory from science to design, and the assumption that the translation of scientific material occurred principally in the design studio.

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maintenance of its accuracy, as a force constraining designers' aesthetic interests, as noted in footnote 7.

Following an analysis of Megaw's work for the group, the chapter then explores the wider resonance of Megaw's diagrams among other key figures involved with the FPG project. They include Hartland Thomas (whose instrumental role in the FPG has escaped interpretation) and others involved in postwar social networks linking fine artists, designers, design reformers, and crystallographers, among whom her diagrams circulated. I argue that Megaw's diagrams appealed to specific modernist impulses in design, art and architectural discourses in which these figures participated. It is in the various cultures of modernism encountered here that we find the roots of the project's aesthetic mission to produce patterns based on scientific diagrams. This chapter's exploration of the reception of Megaw's diagrams within these networks generates insights on why practitioners in cultures outside of crystallography (in fine art and design circles) were interested in crystallographic diagrams and on how they received this scientific material. In addition to contributing to this chapter's reassessment of the history of the FPG, these insights enrich understanding of both the history of postwar British design and of science in postwar British culture.

Methodology and sources

This chapter's inquiry requires an interdisciplinary approach. It analyses the diagrams involved in the project in detail, drawing upon research on scientific visualisation (building particularly chapter one's analysis of crystallographic practice). I also explore encounters that took place between the diagram and aesthetic and ideological frameworks active in postwar design, art and science circles. This chapter therefore also draws on relevant art and design history scholarship and primary sources, beyond a narrowly-defined CoID and Festival focus.

The artefacts at the centre of this chapter are diagrams: primarily Megaw's working drawings and dyelines of her final diagrams submitted to the FPG. I approach these diagrams as objects. As I explained in chapter one, crystallographic diagrams operated as interactive objects similarly to three-dimensional models in that their materiality and manipulation in space were central to their construction and use. They are also *things* here, moving through the post among a discrete network, or shifting around on a work surface, as media such as tracing paper and the photographic print allowed for their physical manipulation[9].

Network models help to trace the encounters and interactions between people and diagrams in this chapter. It is influenced by actor-network-theory (ANT), an approach originated in the 1980s within the sociology of science and technology to study the production of scientific knowledge[10], as well as more recent thinking on networks of human and non-human actors by political theorist Jane Bennett[11]. These approaches see networks of *actors* (including things, people and ideas) as comprising institutions, organisations and other entities. They are not necessarily networks existing in the world in the sense that the noun 'network' is commonly used (although they can be, and in fact, social networks linking actors in various fields figure into the network traced in this chapter)[12]. Network theories afford descriptions of entities such as 'the government' or events such as an electrical blackout as, in John Law's words, 'a heterogeneous set of bits and pieces each with its own inclinations'[13].

This chapter traces a network. The network in this chapter corresponds to

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[9] Alongside the attention upon *things* in recent humanities discourse, a revival of interest in the image is also apparent, hastened by the rise of digital and online media where the visual reigns. But this thinking does not make for a good fit with the subject matter at hand; these diagrams did not *move* with the ease of those of our contemporary digital environment. On the recent resonance of the image in humanities research see *The Visual Culture Reader*, ed. by Nicholas Mirzoeff (Abingdon: Routledge 2013); *Revisualizing Visual Culture*, ed. by Chris Bailey and Hazel Gardiner (Farnham: Ashgate, 2010).

[10] Key texts on and employing ANT include Bruno Latour, *Reassembling the Social: An Introduction to Actor-Network Theory* (Oxford: Oxford University Press, 2005); John Law, 'Notes on the Theory of the Actor-Network: Ordering, Strategy and Heterogeneity', *Systems Practice*, 5 (1992), 379-393; Bruno Latour, *The Pasteurization of France* (Cambridge, Massachusetts: Harvard University Press, 1988); Latour and Woolgar.

[11] Jane Bennett, *Vibrant Matter: A Political Ecology of Things* (Durham: Duke University Press, 2010).

[12] Actual networks have been a part of the networks traced by authors employing such a model. Examples include historian of technology Thomas Hughes' account of the development of electrical power systems in which he develops the notion of technologies as 'systems', which he describes as 'structures comprised of interacting, interconnected components'. More recently, Bennett analyses a widespread North American electrical blackout in 2003 that she sees as emergent from an 'assemblage' of actors including an actual network, the electrical power grid. (Regarding the term 'assemblage' in Bennett's quote, this is her terminology used in place of 'network'. It draws on Gilles Deleuze and Felix Guattari's use of the term, in order to capture the sense of 'ad hoc groupings of diverse elements' in which agency is 'emergent'). Thomas P. Hughes, *Networks of Power: Electrification in Western Society 1880-1930* (Baltimore: Johns Hopkins University Press, 1984), p. ix; Bennett, pp. 23-4.

[13] Law, 'Notes on the Theory of the Actor-Network', p. 386.

what Bruno Latour describes as a 'string of actions where each participant is treated as a full-blown mediator'[14]. I examine the conditions of the interactions between people, diagrams and ideas that are important to this chapter's study of exchange between science and design. In network models, human agency is not necessarily privileged above that of non-human actors. This is relevant to my exploration, for the diagrams acted as mediators of interactions as much as the people involved.

This chapter reflects research carried out into several archival and primary sources including Megaw's FPG archive at the V&A Archives of Art and Design (AAD) and her personal and scientific papers at Girton College, Cambridge (GCPP); FPG documents and other Festival materials held in the AAD and the Design Council Archives (DCA); Kathleen Lonsdale's papers at the National Archives; and Mark Hartland Thomas's postwar writings.

Background

Before beginning this chapter's analysis it is necessary to introduce general background information on the FPG and the Festival where its prototypes debuted.

The Festival of Britain was organised by a collection of prominent figures from industrial design, architecture and science fields under the directorship of the newspaper editor Gerald Barry. They aimed to promote British trade to stimulate the postwar economy, and to educate and engineer the taste of the population[15]. The Festival was also to act, in Barry's much-quoted words, as a

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[14] Bruno Latour, *Reassembling the Social*, p. 128.
[15] Literature on the Festival of Britain includes Atkinson; Paul Rennie, *Festival of Britain Design* (Woodbridge: Antique Collectors' Club, 2007); Conekin, '*The Autobiography of a Nation'*; Mariel Grant, '"Working For the Yankee Dollar": Tourism and the Festival of Britain as a Stimuli for Recovery', *Journal of British Studies*, 45 (July 2006), 581-601; Jo Littler, ''Festering Britain': The 1951 Festival of Britain, Decolonisation and the Representation of the Commonwealth', in *Visual Culture and Decolonisation in Britain*, ed. by Simon Faulkner and Anandi Ramamurthy (Hampshire: Ashgate, 2006), pp. 22-42; *Twentieth Century Architecture 5: Festival of Britain*, ed. by Elaine Harwood and Alan Powers (London: The Twentieth Century Society, 2001); Conekin, 'Here Is the Modern World Itself'; *A Tonic To the Nation: The Festival of Britain 1951*, ed. by Mary Banham and Bevis Hillier (London: Thames and Hudson, 1976); Michael Frayn, 'Festival', in *Age of Austerity*, ed. by Michael Sissons and Philip French (Westport, Connecticut: Greenwood, 1976). See also David Kynaston, *Family Britain 1951-57* (London: Bloomsbury, 2009).

'tonic' to a nation still suffering the economic, physical and emotional devastations of war only six years after its conclusion[16]. The Festival celebrated British developments in industry, science and the arts, and in this national focus was both future-gazing and nostalgic[17].

The Festival took place at sites throughout the UK, with its main site on the South Bank of the Thames in London, which included the Royal Festival Hall and the futuristic, saucer-shaped Dome of Discovery, which housed science exhibits. Land Travelling and Sea Travelling Exhibitions visited additional locations across the country. It ran between May and September 1951, during which time eight-and-a-half million people visited the South Bank site.

The Festival was modelled on a prewar Swedish national exhibition, the 1930 Stockholm Exhibition, which promoted modernist architecture and ideals. The 1951 Festival was also a modernist project in that it displayed social democratic intentions and was, for much of the British public who visited, the first introduction to modernist architecture. Through the erection of public architecture and exhibitions of industry, science, design, art and agriculture, the organisers believed they were extending an education to all classes.

Scientific themes ran through several Festival exhibits: the South Bank's Dome of Discovery concentrated on scientific applications, the Exhibition of Industrial Power in Glasgow covered atomic power in its 'Hall of the Future', and the Exhibition of Science staged in a wing of the Science Museum in South Kensington exhibited 'pure science'[18]. The latter focused on the history of British discoveries concerning the structure of matter[19].

The FPG, however, was organised as part of the Festival's industrial design remit rather than within the planning of the science exhibits. The CoID, then directed by the furniture designer, manufacturer and 'good design' reformer Gordon Russell, presided over the design displays[20]. The Festival supported the CoID's overall postwar programme to promote 'good design' to British

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[16] *A Tonic To the Nation.*
[17] Conekin, '*The Autobiography of a Nation'.*
[18] Jacob Bronowski, *1951 Exhibition of Science South Kensington Guide Catalogue: A Guide to the Story It Tells* (London: H.M. Stationery Office, 1951), p. 5.
[19] I return in more detail to the subject of the Festival's science exhibitions in chapter three.
[20] On Russell, see his autobiography: Russell, *Designer's Trade.*

consumers and to showcase homegrown innovations in industrial design for export to an audience that was expected to include international visitors.

The CoID had been established in 1944 by the Board of Trade. The postwar Labour government targeted industrial design as part of its economic planning efforts, aimed at boosting the country's struggling export trade, which had seen a reduction by two-thirds during the war[21]. An independent organisation, the CoID was charged with fostering 'the improvement of design in the products of British industry'[22]. It agitated for 'good design' within industry and among British consumers through print publications, broadcasting and exhibitions, such as the Festival[23].

Hartland Thomas of the CoID initiated the FPG. He was on the Festival's Presentation Panel, a planning committee devoted to the exhibition's design, and was responsible for industrial design exhibits at the Festival[24]. He developed the idea for the FPG after attending a talk by Kathleen Lonsdale at a 1949 event organised by the Society of Industrial Artists (SIA), a professional association for industrial and graphic designers. At the lecture, Lonsdale showed crystallographic diagrams made by Megaw specifically with the idea in mind that they might be translated into pattern design. Megaw had produced the diagrams for an informal proposal she put to the design consultancy, the Design Research Unit (DRU), in 1946, in which she suggested that crystallographic diagrams be used as the basis for textile and wallpaper patterns (I will discuss Megaw's communication with the DRU and Lonsdale's presentation of her diagrams to the

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[21] Alan Booth, *The British Economy in the Twentieth Century* (Basingstoke: Palgrave, 2001); Ina Sweininger-Bargielowska, *Austerity in Britain: Rationing, Controls, and Consumption 1939-1955* (Oxford: Oxford University Press, 2000); Paddy Maguire, 'Designs on Reconstruction: British Business, Market Structures and the Role of Design in Post-War Recovery', *Journal of Design History*, 4 (1) (1991), 15-30.

[22] Council of Industrial Design, *Council of Industrial Design First Annual Report 1945-1946* (London: H.M. Stationery Office, 1946), p. 5.

[23] Buckley; Whitworth; Jones, 'Design and the Domestic Persuader'; Hayward; *Design and Cultural Politics in Postwar Britain: The Britain Can Make It Exhibition of 1946*; Jonathan M. Woodham, 'Managing British Design Reform I: Fresh Perspectives on the Early Years of the Council of Industrial Design', *Journal of Design History*, 9 (1) (1996), 55-65; Jonathan M. Woodham, 'Managing British Design Reform II: The Film "Deadly Lampshade": An Ill-fated Episode in the Politics of 'Good Taste'', *Journal of Design History*, 9 (2) (1996), 101-115; *Utility Reassessed*; Attfield, *Bringing Modernity Home*; *Did Britain Make It?: British Design in Context 1946-86*, ed. by Penny Sparke, (London: The Design Council, 1986); Gordon Russell, *Designer's Trade: The Autobiography of Gordon Russell* (London: Allen & Unwin, 1968)

[24] Hartland Thomas was responsible for the CoID's enormous 'Stock List' for the Festival, a compendium of objects that were approved as 'good design', and which were exhibited throughout the Festival. By the time of the Festival the list included 20 000 objects. Atkinson; Jackson, *From Atoms to Patterns*.

SIA later in the chapter). Hartland Thomas was interested in the possibilities of Megaw's diagrams as sources for pattern design, and wrote to Megaw soon after this lecture, initiating a process that resulted in the FPG:

> Mrs. Lonsdale showed, at the end of her lecture, some transcriptions of crystallographic diagrams that she told us you had prepared with the idea that they might be used directly as decorative patterns of more than decorative interest in textile printing or pottery transfers, or the like. Some of these seem to us to be very promising, and I wonder whether you would be interested for me to see whether we can place any of these patterns with manufacturers?[25]

That summer Hartland Thomas began assembling manufacturers to take part in the project with a view to launching their products at the Festival. For the FPG project, Hartland Thomas partnered with the interior designer of the Dome of Discovery's Regatta Restaurant, Misha Black, and his collaborator Alexander Gibson. They agreed to use FPG prototypes throughout the restaurant. Over the next year and a half of preparation, Hartland Thomas liaised consistently with all parties and worked closely with Megaw. The FPG met frequently as a group, usually including Megaw and Black, to discuss the project's direction and individual designs[26].

The FPG's prototypes were spread out throughout the Festival and primarily showcased in use (aside from a small display of FPG products in the Dome of Discovery and the Land Travelling exhibition)[27]. The Dome's Regatta Restaurant was the FPG's true home at the Festival. It was fully appointed with FPG prototypes (Figure 1). The FPG's contributions included its menus, curtains, carpet, and waitresses' collars (Figure 2)[28]. The Regatta Restaurant also housed a small display of FPG samples with a brief text on the project. Additionally, FPG patterns served as part of the exhibition design (such as wallpaper used as display backgrounds) in the Dome of Discovery and South Kensington's Exhibition of

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[25] Mark Hartland Thomas to Helen Megaw, 1 June 1949. DCA 5384.
[26] Several authors have described this series of events leading to the FPG's organisation. The most comprehensive is the account in Jackson, *From Atoms to Patterns*.
[27] The manner of the presentation of the FPG at the Festival may reflect the CoID's lack of enthusiasm for the FPG's designs themselves. This lack of enthusiasm is discussed in chapter three, in which I argue that the FPG is not necessarily reflective of the CoID's overarching goals at the Festival.
[28] For a detailed description of the FPG's display at the Festival see Jackson, *From Atoms to Patterns*.

Science (Figure 3). An illustrated guide to the FPG, *The Souvenir Book of Crystal Designs*, was sold at the Festival[29] (Figure 4). It includes images of several FPG products, their source diagrams by Megaw, and text by Hartland Thomas narrating the group's formation.

Figure 1 Interior of the Regatta Restaurant.

Figure 2 Lace collar based on the crystal structure of the mineral hydrargillite for Regatta Restaurant waitresses designed by H. Webster for A.C. Gill.

[29] Mark Hartland Thomas, *The Souvenir Book of Crystal Designs* (London: CoID, 1951).

Figure 3 Seats in the Exhibition of Science's cinema upholstered with fabric by ICI produced for the FPG.

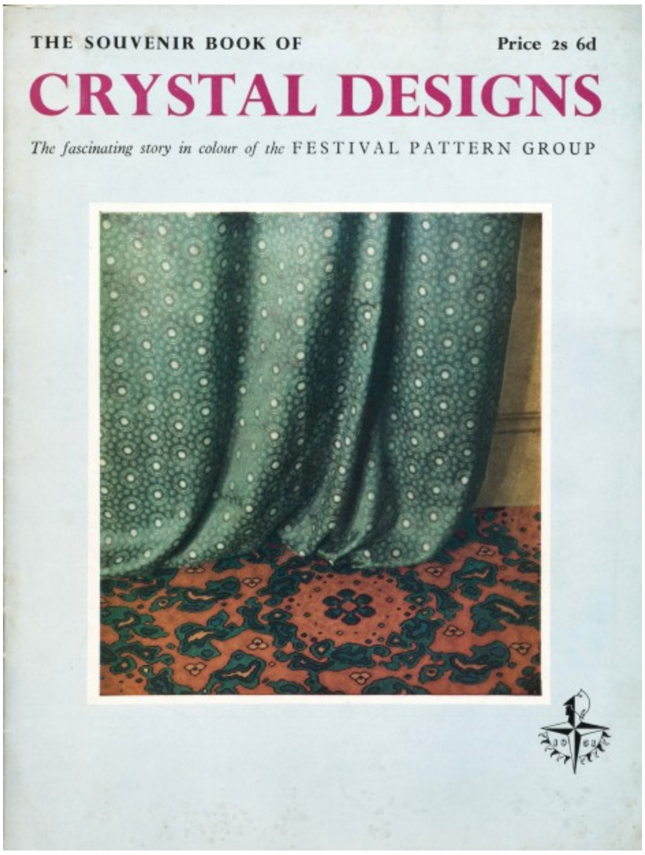

Figure 4 Front cover of *The Souvenir Book*.

1. Helen Megaw: Designer of diagrams

This section focuses on Megaw's selection and production of diagrams for the FPG and demonstrates that her role was more complex and instrumental to the project than has been acknowledged. In *The Souvenir Book*, Hartland Thomas described Megaw's contribution to the group as 'the essential one of supplying the crystal structure diagrams'[30]. This echoes the terms of Megaw's contracted role as the FPG's official 'Adviser on Crystal Structure Diagrams', which stipulated that she was to provide 'an adequate supply' of diagrams[31]. The word 'supply', however, with its connotation of passive conveyance, severely understates Megaw's FPG work. I argue that the diagrams the group received, and which formed a strong basis for its designs, were mediated by Megaw in ways conditioned by her taste in, and specific conceptions of, design. Yet she did so with such subtlety and seeming ease, and in a way that was so continuous with her scientific practice, that so far it has gone unnoticed. The fact that this has not been identified is also a product of the disciplinary perspectives from which the FPG has been studied, as I explain in the analysis.

Born in Dublin in 1907, Megaw's specialism as a crystallographer was mineralogy. She completed her PhD at Cambridge in 1934 under Bernal. Early in her career, Megaw conducted research on ice (which resulted in the naming of Megaw Island in Antarctica after her), and then turned her attention to minerals with ferroelectric properties[32]. She spent most of her career at the Cavendish, as Assistant Director of Research in Crystallography from 1949-59 and Fellow,

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[30] Hartland Thomas, *The Souvenir Book*, p. 2.
[31] John Weyman [Chief Administrative Officer of the CoID] to Helen Megaw, 6 January 1950. DCA 1466.
[32] Ferroelectricity is a property associated with spontaneous electrical polarisation. Crystals with this property have been used in many applications including their deployment as capacitors and use in memory storage technologies. Work towards these applications was hastened by research beginning in the mid-twentieth century on minerals possessing the perovskite structure, to which Megaw was a key contributor. Megaw published the first book on this subject in 1957: Helen D. Megaw, *Ferroelectricity in Crystals* (London: Methuan, 1957). A.M. Glazer, 'Megaw, Helen Dick (1907-2002)', in *Oxford Dictionary of National Biography*, ed. by Lawrence Goldman (Oxford: Oxford University Press, 2009), pp. 712-714.

Lecturer and Director of Studies in Physical Science at Girton College, a Cambridge women's college, until her retirement in 1972[33].

Megaw was the FPG's gateway to the crystallography community's expertise, their pool of structure data and knowledge of how it was visualised. In addition to providing diagrams, she described to the group the conventions X-ray crystallographers used in drawing diagrams and informed them, in accordance with her contract, of 'the limits which designs may be adapted for commercial use while retaining their scientific meaning and accuracy'[34]. (This issue of accuracy re-emerges in discussions later in the chapter).

My analysis of Megaw's work for the FPG focuses on the diagrams she produced for the FPG, so a brief introduction to the kinds of diagrams she submitted is necessary. For these diagrams, Megaw obtained data on structures variously from her own research, published work, unpublished research by colleagues, and structures long-known and considered 'common knowledge' (that is, they were not necessarily associated with a specific scientist)[35]. The information on structures that Megaw sourced was either in the form of existing diagrams or mathematical data, from which she drew a diagram. She submitted several types of diagrams to the group. Most were mineral structures (reflecting Megaw's specialism), rendered in polyhedral or ball-and-spoke projections, which were common conventions for representing mineral structures (Figure 5). She also submitted drawings reflecting other types of diagrams commonly used in X-ray crystallography at the time, including electron density maps (Figure 6), and Patterson plots (Figure 7). In addition to mineral structures, she included biological and chemical structures studied by friends and colleagues, including Kendrew (myoglobin) and Hodgkin (insulin).

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[33] Megaw was the first woman on staff at the Cavendish. J. G. Crowther, *The Cavendish Laboratory, 1874-1974* (New York: Science History Publications, 1974).
[34] John Weyman to Helen Megaw, 6 January 1950. DCA 1466.
[35] Helen Megaw to Brigid O'Donovan, 8 December 1949. AAD 1977/3/60.

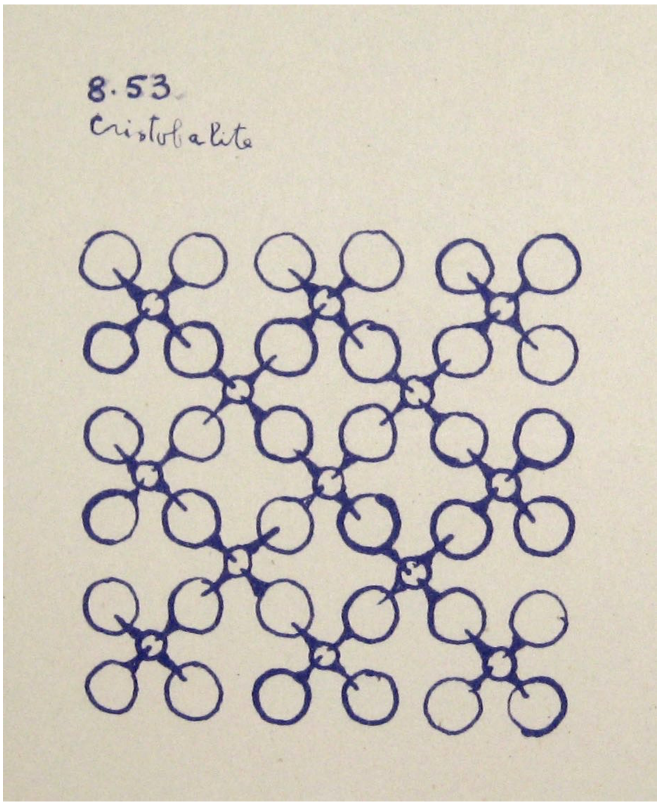

Figure 5 Dyeline of a diagram of the mineral cristobalite submitted by Megaw to the FPG (detail).

Figure 6 Print of an electron density map diagram of the mineral afwillite submitted to the FPG by Megaw.

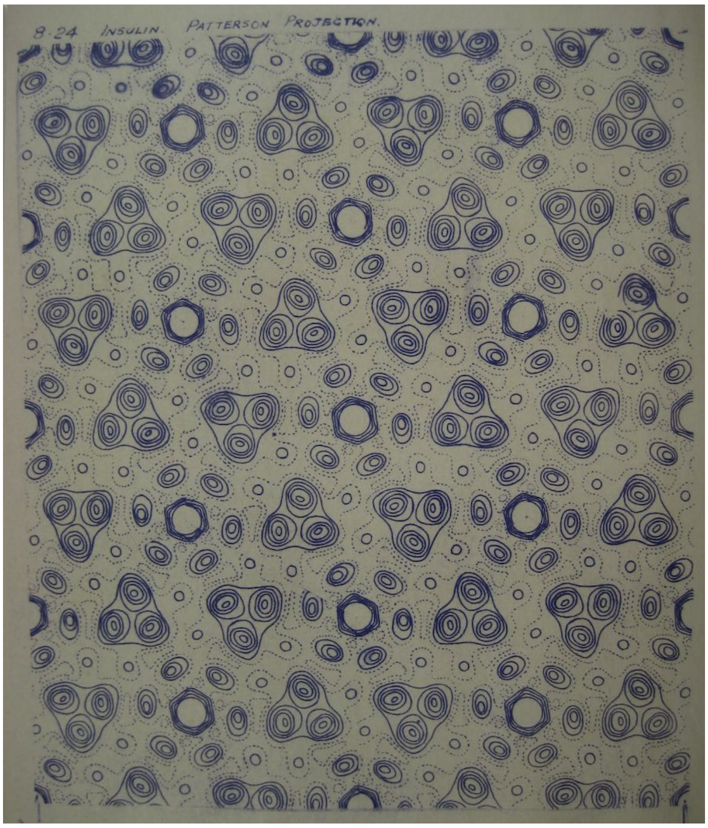

Figure 7 Dyeline of a Patterson projection diagram of insulin submitted by Megaw to the FPG.

An 'attractive' diagram

Megaw's selection of diagrams for the group constitutes an important way in which she shaped the FPG project. It is a key area in which I argue that her conception of design affected her FPG work. Reflecting on her participation in the FPG decades later, Megaw recalled selecting structures that, she wrote, 'I thought would be attractive'[36]. This statement suggests a point that becomes clear throughout this analysis: Megaw conceived of diagrams not only as scientific but also as potentially decorative objects. And as such, they were subject to judgments about what makes a pleasurable or, in a particular view, *good* object. In other words, they are subject to judgments based on taste.

The issue of taste consequently arises here in a somewhat unconventional topic area for questions of taste: the scientific diagram. This has not been explored in previous histories of the FPG. Historians are aware of Megaw's

[36] Helen D. Megaw, 'My Recollections of My Connection with the Crystallography Theme in the 1951 Festival of Britain As Written Down in 1993'. GCPP 2/2/23.

visual pleasure in crystallographic diagrams generally, largely through an unpublished essay, ‘Pattern in Crystallography’, that Megaw wrote for the DRU in 1946 in which she expressed ‘an appreciation’ of their patterns[37]. Historians note that she ‘was delighted’ by the ‘beauty and symmetry’ of crystal structures, or cite Megaw’s ‘instinctive appreciation’ of diagrams and her ‘good eye’ for choosing diagrams for the FPG[38]. What this section explores is a significantly different matter. My analyses will show that Megaw’s taste determined the formal character of diagrams she selected for the FPG in specific ways, and that her taste, as sociologists and design historians demonstrate of taste in other areas, was socially conditioned[39]. The next several sections describe how Megaw’s judgment of what made a diagram ‘attractive’ shaped the types of structures she submitted to the FPG and her manipulation of their visual form. I move from close analysis of her working drawings and submitted diagrams to illumination of the social underpinnings of Megaw’s taste and notion of the decorative.

I begin with Megaw’s selection of structures. An instance in which she expressed her *distaste* for a particular structure provides a way in to understanding her formal criteria for an ‘attractive’ diagram (to use her term from the quote above). In 1950 Hartland Thomas conveyed a request to Megaw from the Festival’s Science Directorate for diagrams of some new synthetics, including nylon, for use in the display design of the Exhibition of Science[40]. She responded, unenthusiastically, that a nylon diagram would be ‘rather dull and drab’[41].

What made a ‘dull’ diagram in Megaw’s view? The diagram of nylon’s structure published by its researcher, the ICI Laboratories chemist and

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[37] Helen Megaw, ‘Pattern in Crystallography’, November 1946. DCA 1466.

[38] Forgan, ‘Festivals of Science’, p. 229; Jackson, *From Atoms to Patterns*, pp. 7, 15.

[39] Design history texts on gender, class and other social factors underpinning questions of taste include Attfield, *Bringing Modernity Home*; David Brett, *Rethinking Decoration*; Sparke, *As Long As It’s Pink*; Dick Hebdige, *Hiding in the Light: On Images and Things* (Routledge, London, 1988). Much design history in this area draws upon sociological literature that develops an understanding of taste as linked with social conditions such as class and educational background. Sociologist Pierre Bourdieu’s 1984 book *Distinction* is key here. Bourdieu described taste as part of one’s *habitus*, which is defined by an individual’s particular ‘disposition’ (which includes manners and lifestyle as well as taste) influenced by one’s social environment. Pierre Bourdieu, *Distinction: A Social Critique of the Judgment of Taste* (Cambridge, MA: Harvard University Press, 1984), p. 170. See also Jukka Gronow, *The Sociology of Taste* (London: Routledge, 1997).

[40] Mark Hartland Thomas to Helen Megaw, 17 February 1950, AAD 1977/3/69. This request was an unusual case; Megaw chose most of the structures for the group herself.

[41] Helen Megaw to Mark Hartland Thomas, 26 February 1950. AAD 1977/3/70.

crystallographer C. W. Bunn (Figure 8), differs from most of the structures Megaw selected herself. Its structure involves a linear, non-polygonal atomic arrangement comprising zigzagging chains of atoms. Megaw's diagram for the FPG of the mineral beryl, on the other hand, is rather different visually, exhibiting features common to many ball-and-spoke structures Megaw selected herself (Figure 9): it exemplifies her preference for more geometrical structures, frequently made up of atoms arranged into polygons, which form intricate nets of atoms. The unit cell (the most basic unit of a crystal's repeating pattern) in the diagram of beryl comprises two hexagonal rings of tetrahedra formed of silicon and oxygen atoms at different elevations in the structure. Such arrangements of atoms might be extended to cover the page (as Megaw has done in the beryl diagram) in comparison to the vertical, more linear chains of atoms in the diagram of a polymer such as nylon.

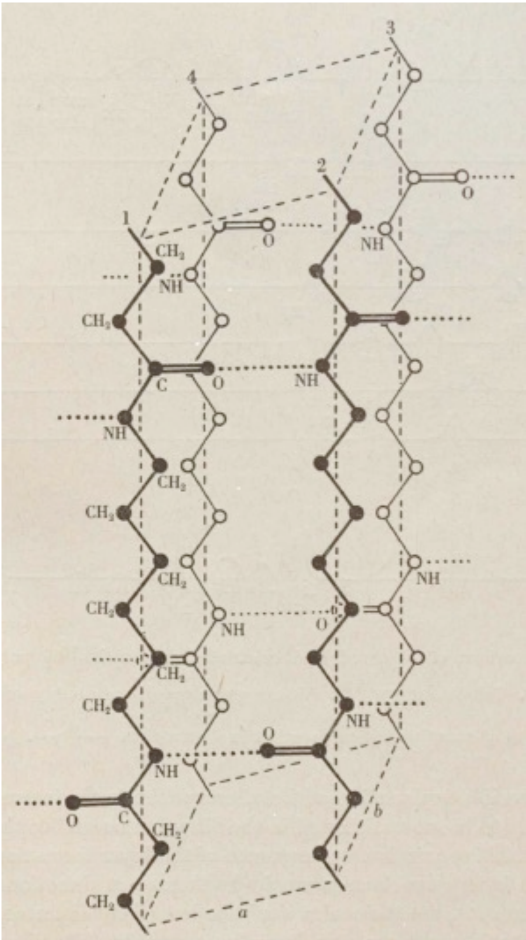

FIGURE 13. Structure of α crystal of 66 polyamide.

Figure 8 Nylon diagram published by C.W. Bunn in 1947.

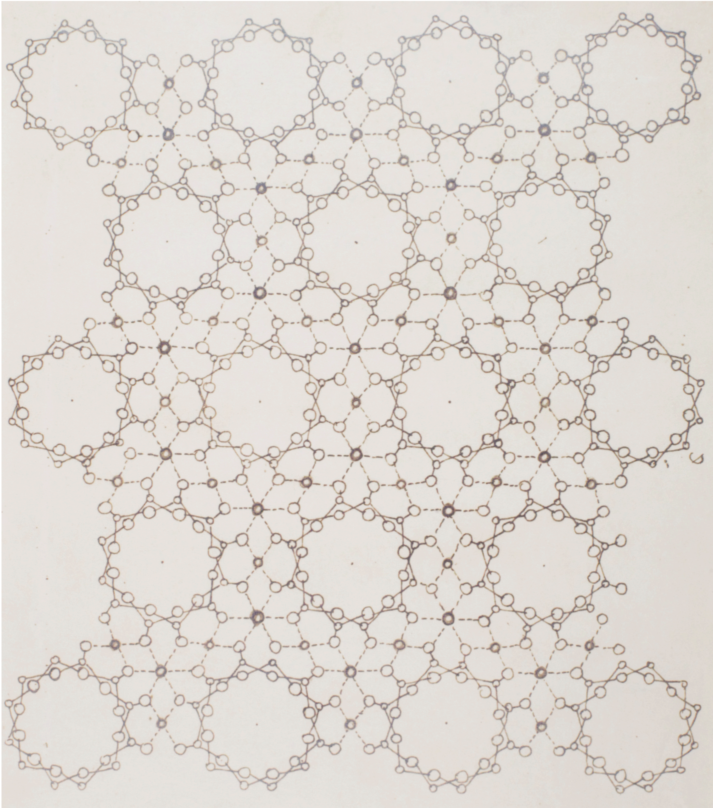

Figure 9 Beryl diagram by Megaw for the FPG.

Nylon's structure is symmetrical across only two axes, meaning it does not contain a high order of rotational symmetry, a feature of many structures selected by Megaw. A structure with a higher order of rotational symmetry, the beryl unit cell, for instance, is symmetrical across many axes (you can draw lines of symmetry through the unit cell at several points). An important idea here is that rotational symmetry is not only applicable to the topic of crystal structures. It can be found also in pattern design. In fact, a high degree of rotational symmetry is common in pattern design, especially for textiles, because a low degree of rotational symmetry restricts the orientations in which the material can be used, making it difficult to work with in sewing, upholstery and other such practices employing textiles. In this sense, the crystal structures Megaw deemed 'attractive' exhibit a convention of decorative design.

Although it was not to her taste, Megaw reluctantly accepted the request for the nylon structure diagram, writing, 'perhaps with careful attention to thickness of lines, sizes of circles, and such-like factors it could be made reasonably decorative'[42]. A nylon diagram she submitted to the FPG repeats several layers of the chain seen in Bunn's diagram and renders atoms as larger circles, generating a composition closer to the polygonal arrangements common to the crystal structures Megaw favoured (Figure 10).

Megaw's nylon diagram thus accentuates the very stylistic elements enumerated in her letter. This suggests that her statement was not meant as advice to designers. Megaw was describing *her* plan for constructing a diagram of nylon. She saw the act of transforming nylon's structure into something 'reasonably decorative' as her responsibility. This points to a larger feature of Megaw's process: her formal manipulation of the diagrams themselves, through which she aimed at the production of a 'decorative' diagram. This is explored in the next section.

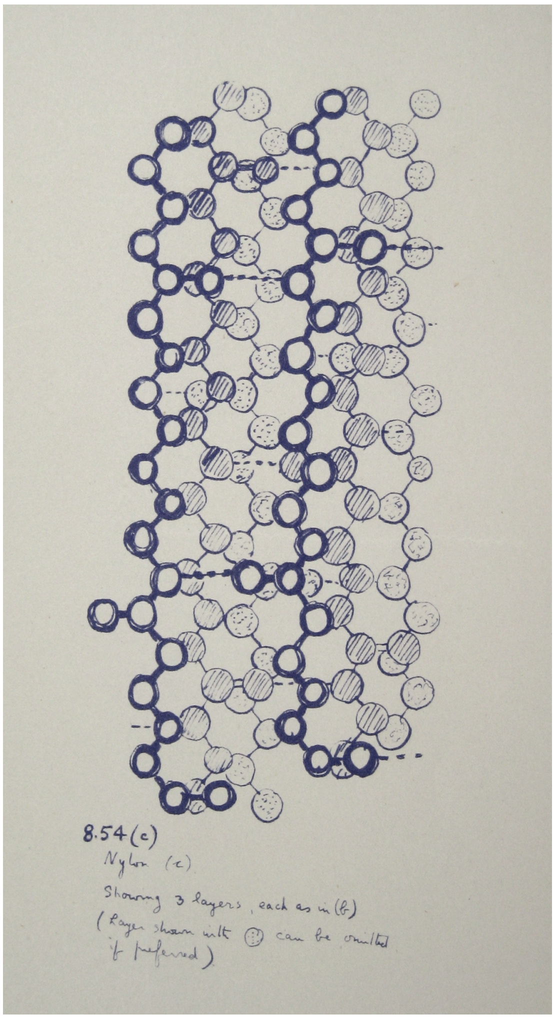

Figure 10 A diagram of nylon submitted by Megaw to the FPG.

[42] Helen Megaw to Mark Hartland Thomas, 26 February 1950. AAD 1977/3/70.

Making diagrams decorative

This section shows that Megaw took it upon herself to make many diagrams more 'decorative' when composing them for the FPG. It identifies formal choices and alterations Megaw made when preparing these diagrams. The following sections will argue that these reveal a specific conception of decorative art at work associated with the South Kensington mode of ornamental drawing. These diagrams show that as a scientist, Megaw had absorbed non-scientific aesthetic models, which she applied to scientific diagrams.

Historians have not pursued this aspect of the cultural transmission of diagrams within the FPG, even though Megaw notes this fact in supplementary information she provided to the FPG about the diagrams they received. She wrote:

> All the diagrams under consideration have actually arisen in the course of scientific work, though the particular way of displaying them is such as to put more emphasis on their decorative aspects[43]

Megaw is eager to explain that the diagrams are indeed reflective of 'scientific work' (that is, the structural knowledge the diagrams represent arose from research, rather than the particular diagrams themselves, which were drawn specifically for the FPG). This is perhaps because many of the diagrams she submitted *looked* decorative.

Megaw did not provide any more detail on the issue. A close examination of her process, however, is revealing. The operation Megaw performed most frequently upon the composition of a diagram, whether she was drawing from mathematical data, copying, or tracing an existing diagram, was the repetition of a unit cell. Many of Megaw's drawings of crystal structures for the FPG see her repeating the most fundamental unit of a structure's symmetry over and over, sometimes covering an entire page. This is evident in the insulin (Figure 7) and beryl (Figure 9) dyelines above, and the afwillite diagram below (Figure 11).

[43] 'Dr. Megaw's Notes on Crystal Structure Diagrams', 12 January 1950. DCA 5396.

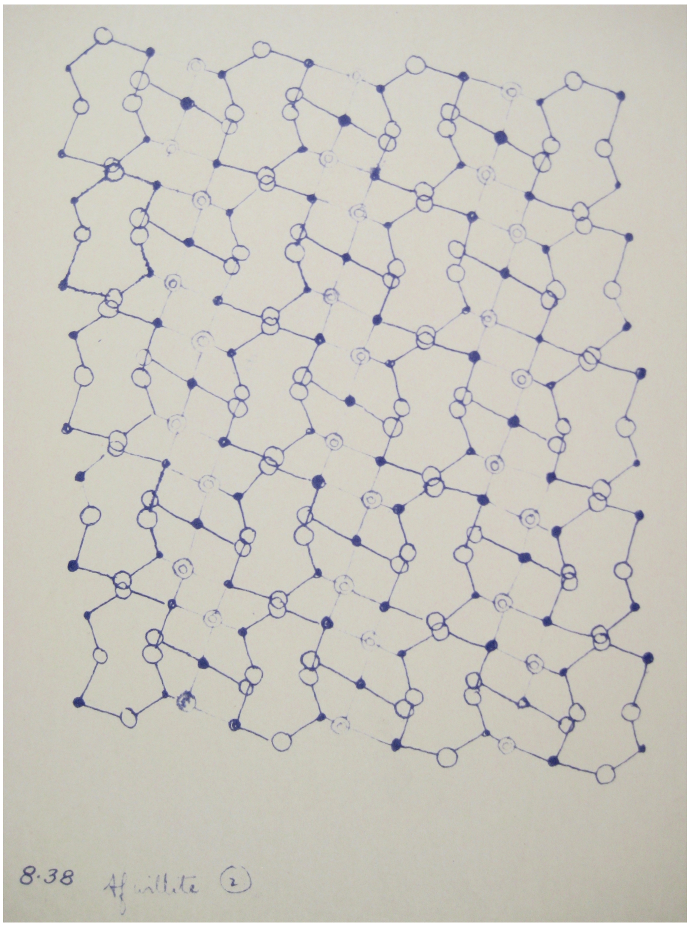

Figure 11 A dyeline of a diagram of afwillite that Megaw submitted to the FPG.

In scientific practice it is unnecessary to extend a crystal structure diagram or model to include so many unit cell repeats in order to understand or communicate data about a structure, so it was not commonly done. If a single unit is repeated at all in a diagram, typically only the most immediate sections of the surrounding four or five units are included in order to indicate their manner of attachment to one another, as in the beryl diagram published by the structure's crystallographer W.L. Bragg (Figure 12). There is simply no additional scientific information offered by the diagram if more repeats are included.

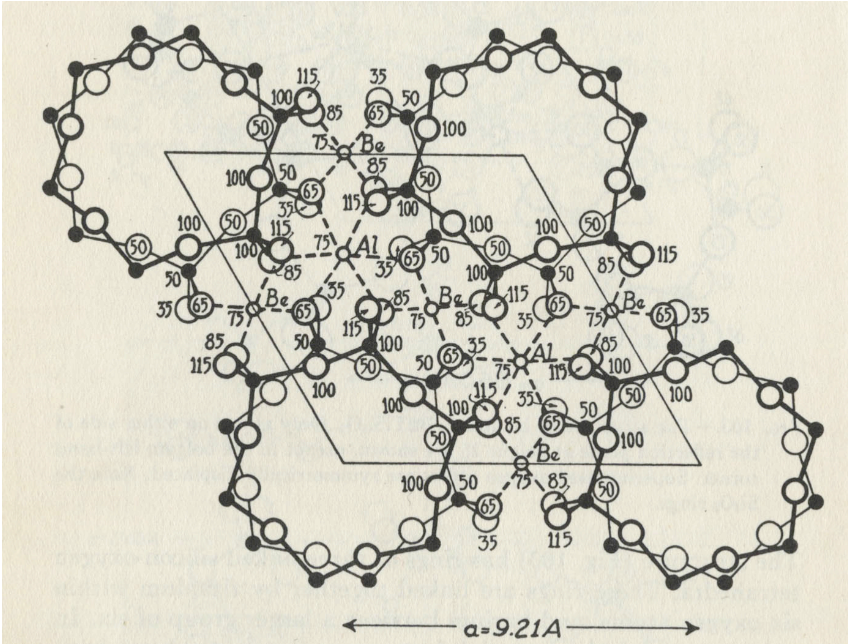

Figure 12 Diagram of beryl structure published in Bragg's 1937 book, *Atomic Structure of Minerals*.

Yet this is precisely what Megaw has done in many of the final diagrams submitted to FPG designers. Forgan views the repetition in Megaw's diagrams as a measure intended to prevent designers from producing inaccurate patterns by linking molecules incorrectly[44]. Accuracy was indeed a concern for Megaw. A handful of repeats, however, would ensure this just as well as continuing right across the page, as she often did.

The shift evident in many of her FPG diagrams - from the scientific diagram's efficient limitation of unnecessary repetition to filling a page with repeated interlinking unit cells - sees the crystallographic diagram transformed by a convention of pattern design: it becomes an 'all-over' pattern. The term is traditionally used to describe a pattern design in which - as one might guess - a motif repeats across an entire surface. This applies frequently to wallpaper or textile patterns because it goes hand-in-hand with the surface printing techniques historically used in their production, in which a wood block or roller (or by the mid-nineteenth century, a mechanical printing apparatus) reproduced a repeating pattern continuously over an entire surface[45].

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[44] Forgan, 'Festivals of Science'.
[45] *The Papered Wall: The History, Patterns and Techniques of Wallpaper*, ed. by Lesley Hoskins (London: Thames & Hudson, 2005).

The repetition of the unit cell, like her selection of structures with a high order of rotational symmetry, was a product of Megaw's accentuation of her notion of what was 'decorative'. In some instances, technology for image reproduction helped execute the repeating pattern. Several early diagrams comprise multiple cut-out photographic prints of a repeat unit tiled on a page (Figure 13)[46]. A note in Megaw's archive (in her hand) states that these are probably from the set she produced to accompany her proposal to the DRU in 1946 that they be used for textile and wallpaper pattern design. In her letter to the DRU accompanying the diagrams she wrote, 'I should like to ask designers of wallpapers and fabrics to look at the patterns made available by X-ray crystallography'[47]. It is significant that Megaw's proposal involved 'wallpapers and fabrics', the very types of products in which all-over repeating patterns were common. It suggests that her echoing of the repetition common to such patterns is not merely coincidental. Rather, she had designed objects with repeating patterns in mind when producing the diagrams.

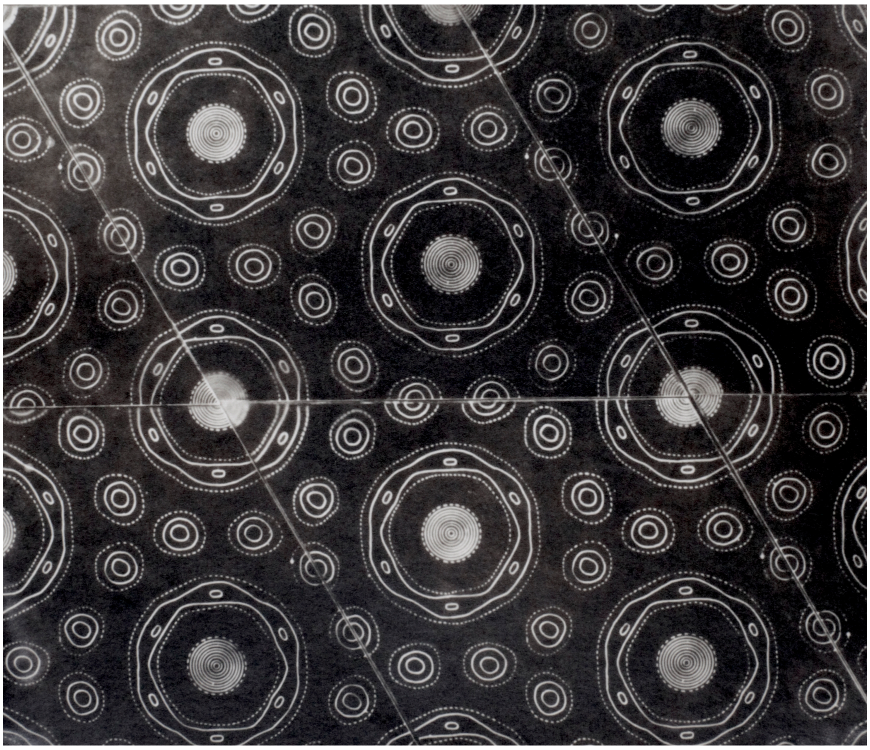

Figure 13 Photographic print of tiled haemoglobin diagram (detail).

[46] There is no way of knowing whether Megaw photographed, cut these out and tiled them herself or had it done by someone else.
[47] Helen Megaw to Marcus Brumwell, 20 February 1946. AAD 1977/3/12.

In mimicking the repetition associated with wallpaper and textile pattern, Megaw's diagrams materialise a pedagogical analogy commonly used by crystallographers. It concerns the fact that a crystal's unit cell theoretically repeats indefinitely. Although crystallographers did not represent this in diagrams, there is a tradition in X-ray crystallography, initiated by W.L. Bragg, of explaining such repetition through an analogy to wallpaper patterns[48]. This is an example of such an explanation from his 1937 crystallography text, *Atomic Structure of Minerals*:

> A crystal is essentially a pattern. The atoms are arranged according to a plan […] Consider a two-dimensional pattern such as a wall paper. Fix attention upon some particular feature such as the tip of a flower in a spray that is repeated again and again. These points will be seen to be arranged on a regular network[49].

Megaw referenced this pedagogical custom in her 1946 'Pattern in Crystallography' essay: 'If our path to the understanding of crystal structures has been made easier for many of us at its outset by the contemplation of wallpapers,' Megaw wrote, 'the crystallographer is now in a position to repay his debt to the wallpaper designer' by offering diagrams as the basis for wallpaper patterns[50]. Because of this essay, historians know that Megaw had this analogy in mind when working with the FPG[51]. But I maintain that it ran more deeply - to the very fabric of the diagrams she produced.

Megaw's representations of the unit cell itself in many FPG diagrams further anticipate their application to pattern design. These are, firstly, distinguished by a devotion to 'flatness', in the sense of an eschewal of the illusion of three-dimensionality. Several conventions of crystallographic drawing in use at the time employed projections representing three-dimensional

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[48] This tradition is referenced frequently by authors on X-ray crystallography, but a detailed interpretation of W.L. Bragg's use of wallpapers as an explanatory tool can be found in Suzanne Black, 'Domesticating the Crystal: Sir Lawrence Bragg and the Aesthetics of "X-ray Analysis"', *Configurations*, 13 (2) (2005), 257-282.

[49] W.L. Bragg, *Atomic Structure of Minerals* (Ithaca: Cornell University Press, 1937), p. 4. Black notes similar descriptions involving wallpaper and other domestic objects in W.L. Bragg's 1975 *The Development of X-ray Analysis* and his *The Crystalline State Volume 1: A General Survey* (London: Bell, 1966). Black, 'Domesticating the Crystal'.

[50] Helen Megaw, 'Pattern in Crystallography'.

[51] Jackson, *From Atoms to Patterns*.

perspective for the purpose of showing spatial relationships. These include perspective ball-and-spoke and solid polyhedra diagrams (illustrated in chapter one). Megaw used these in her scientific work, but in her FPG diagrams she jettisoned their illusion of depth or simply selected a different convention.

A diagram of the structure of minerals classed as perovskites that she submitted to the FPG is an example. There are many ways to represent the perovskite structure (as with all crystal structures) so when it came to preparing a diagram for the FPG, Megaw had several possible conventions to chose from, especially since she was deeply familiar with the subject matter through her own research. Perovskites comprise octahedral arrangements of oxygen atoms (in which oxygen atoms sit at the points describing the octahedra). In her research Megaw frequently used a three-dimensional projection diagram showing the octahedra, because her research concerned their orientation in space (Figure 14 is an example). Yet she chose a different convention for the diagram she prepared for the FPG, one in which the octahedra no longer have the illusion of three-dimensionality, but are instead projected as two-dimensional diamonds interspersed with circles (denoting the oxygen atoms) at their intersections (Figure 15). Having articulated this motif she proceeded, as usual, to repeat it.

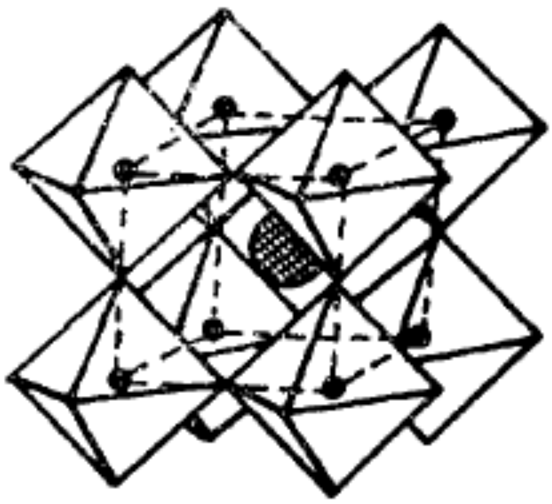

Figure 14 Perovskite structure drawn in projection, published by Megaw in 1946.

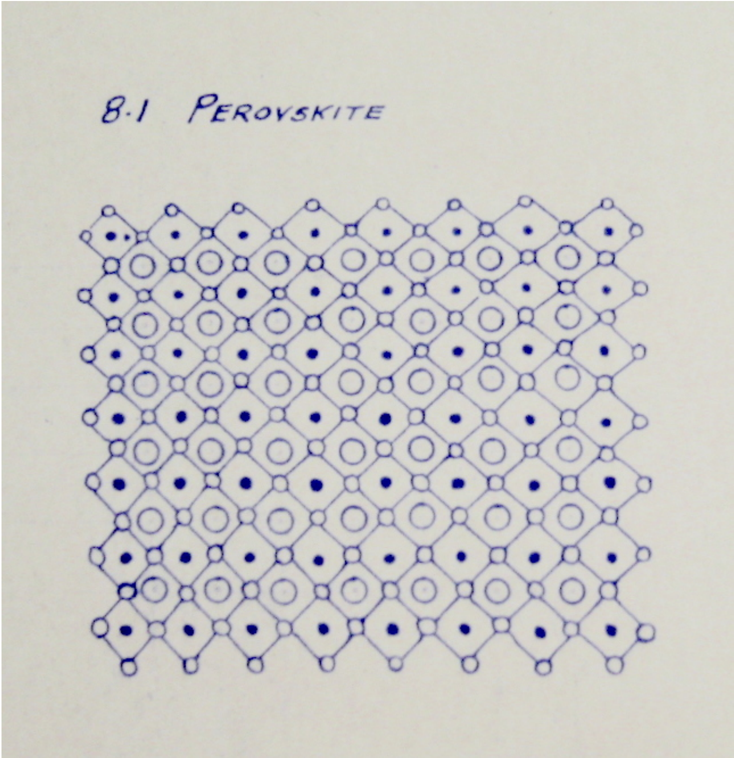

Figure 15 Dyeline of a perovskite diagram prepared by Megaw for the FPG.

The second point concerning Megaw's representations of the unit cell is that her diagrams frequently accentuated the geometry of the repeat unit. Ball-and-spoke diagrams of mineral structures often present symmetrical and geometrical forms (visible in the perovskite and beryl diagrams), especially when rendered in the so-called 'idealised' formation in which the atomic arrangement is pictured as more geometrically regular than it might be in nature. Patterson plots and electron density maps do not always have these qualities (see for example a Patterson diagram of afwillite published by Megaw in 1952, Figure 16). Megaw's compositions of such diagrams for the FPG, however, often submitted them to repeating patterns, which brought out their geometric symmetries. This is clear in the dyeline of insulin, based on a Patterson plot by Hodgkin, in which the diagram's hexagonal unit is repeated (Figure 17). This was a deliberate aesthetic decision. Of Patterson plots and electron density maps, Megaw wrote to a colleague in 1950, 'I myself have been quite surprised how effective a lot of these look when one draws them out to show a large number of repeats, even when the asymmetric unit looks quite undistinguished'[52].

[52] Helen Megaw to Professor John Robertson, 30 January 1950. AAD 1977/3/718.

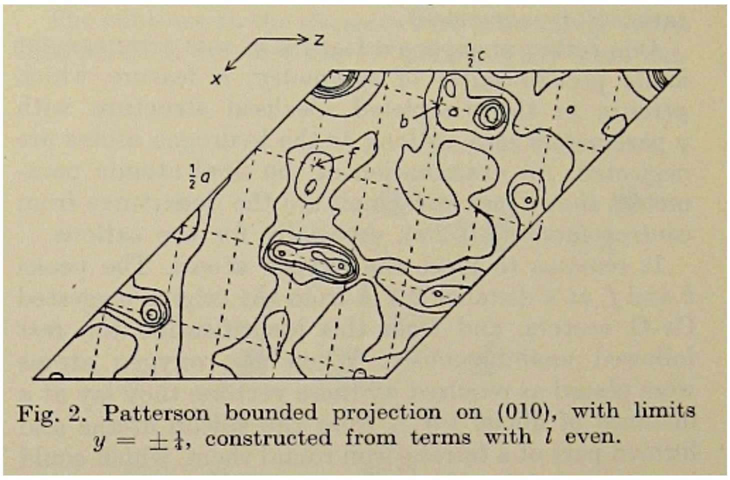

Figure 16 A Patterson diagram of afwillite published by Megaw in 1952.

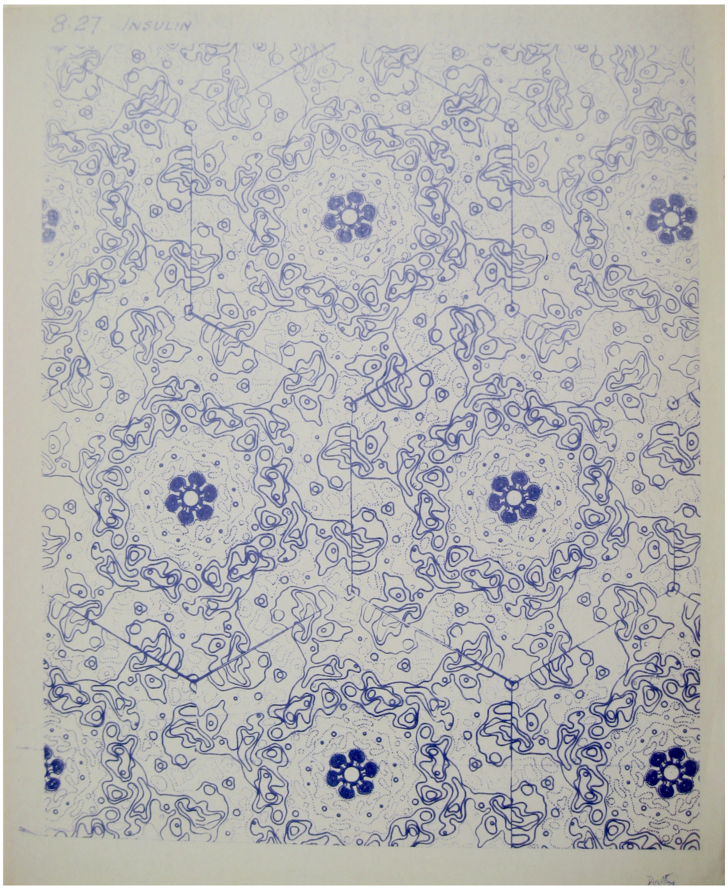

Figure 17 Dyeline of tiled insulin diagram submitted by Megaw to the FPG.

Megaw's working diagrams of the mineral apophyllite further demonstrate her preference for geometric structure. To draw this structure for the FPG, she referred to publications by crystallographers W.H. Taylor and W.L.

Bragg (Figures 18 and 19)[53]. She has included information not included in the ball-and-spoke projection diagrams they published, however: a series of dotted lines limning the tetrahedral formations into which oxygen and silicon atoms are arranged in the apophyllite structure, thus emphasising geometric form (Figures 20 and 21). A second apophyllite diagram Megaw submitted consists only in these flattened tetrahedra, using a convention and limited selection of information that accents flat geometric form (Figure 22). It pictures the structure in the more geometrical 'idealised' formation in which the diagram's constituent shapes appear to be arranged standing straight up rather than in a 'slanted' formation. This was incorporated into the FPG pattern design for laminated plastic sheet manufactured by Warerite, as though it was a ready-made pattern (Figure 23).

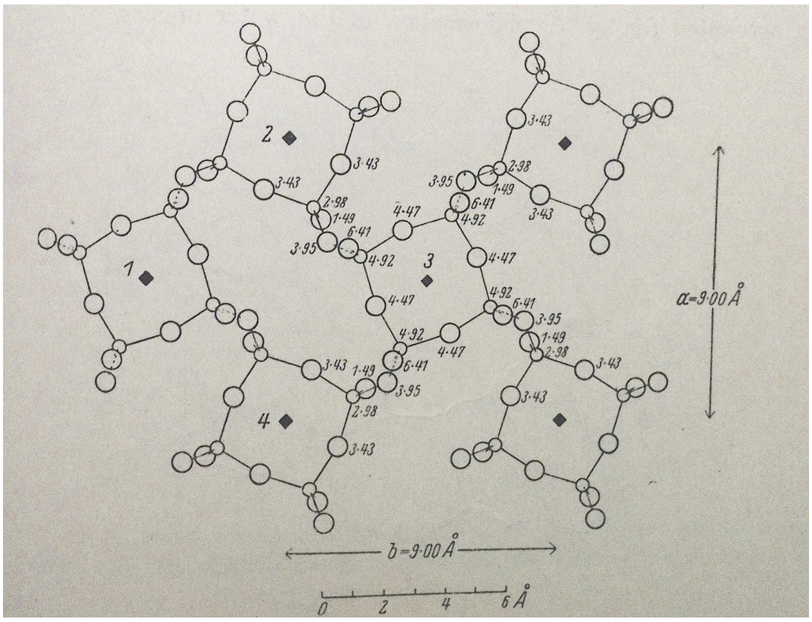

Figure 18 Apophyllite diagram published by W. H. Taylor to which Megaw referred.

[53] Megaw's reference material is noted as well in Jackson, *From Atoms to Patterns*.

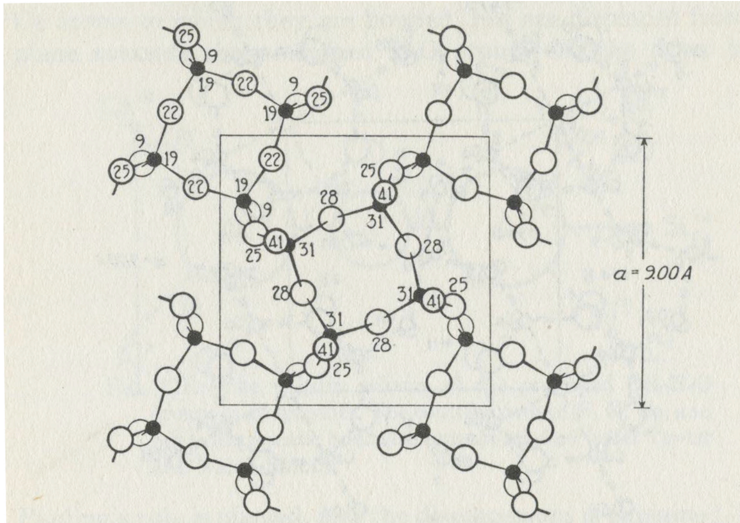

FIG. 125.—The linked silicon-oxygen groups in apophyllite, $KF \cdot Ca_4Si_8O_{20} \cdot 8H_2O$.

Figure 19 Diagram of apophyllite published by Bragg to which Megaw referred.

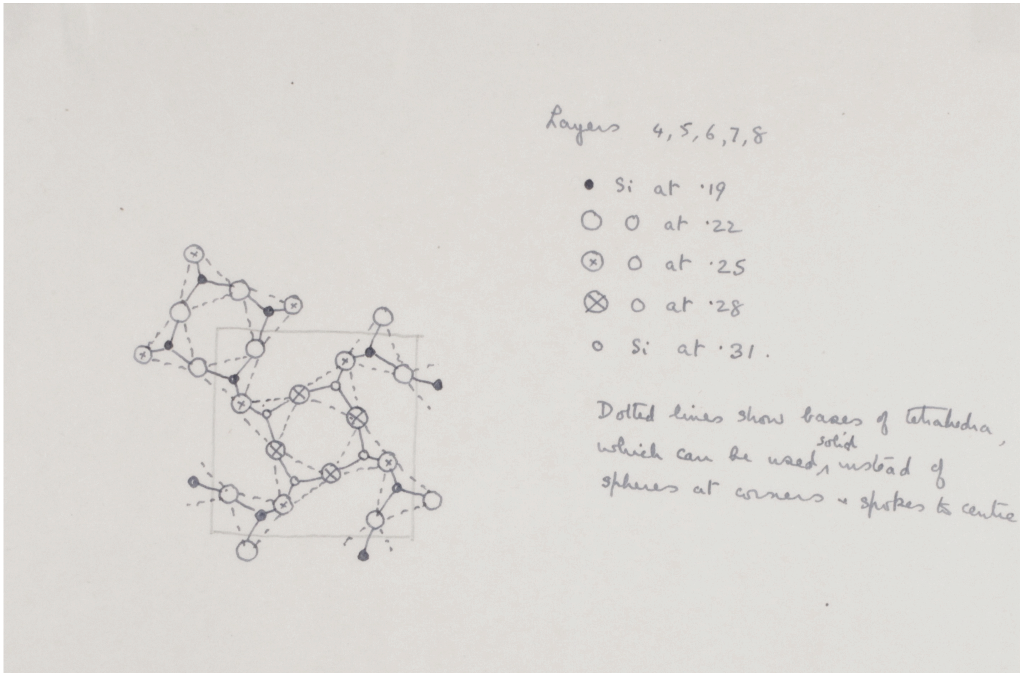

Figure 20 Working diagram of apophyllite structure by Megaw.

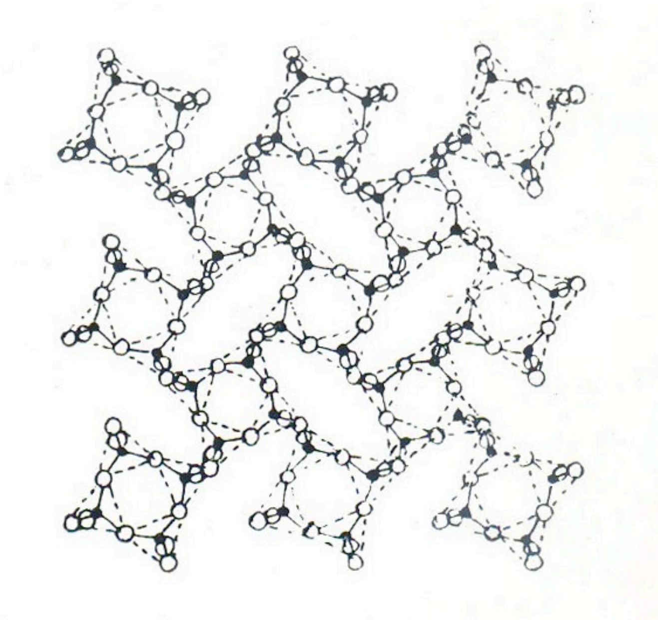

Figure 21 Copy of Megaw's apophyllite diagram submitted to the FPG.

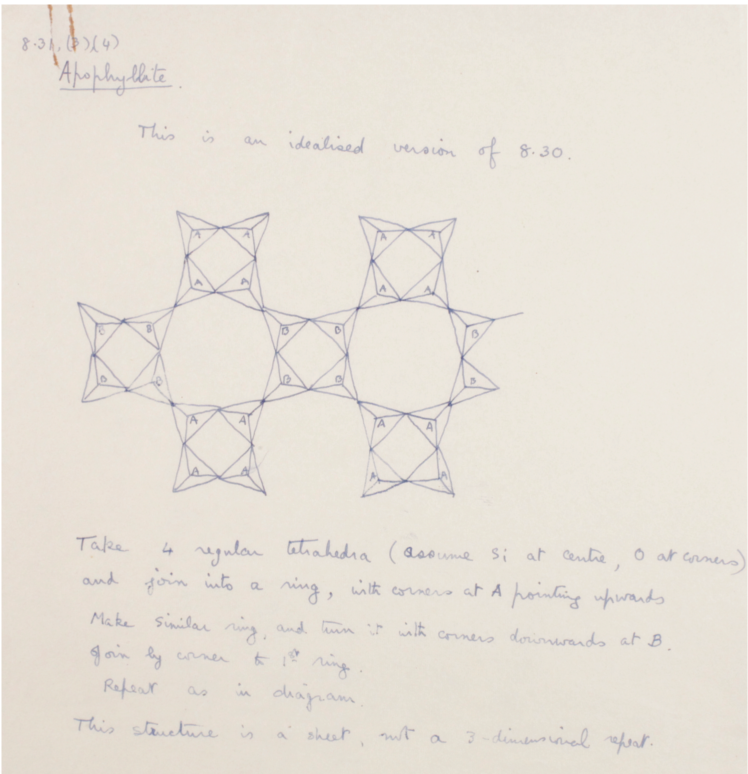

Figure 22 Megaw's working drawing, the basis for a dyeline of apophyllite structure submitted to the FPG.

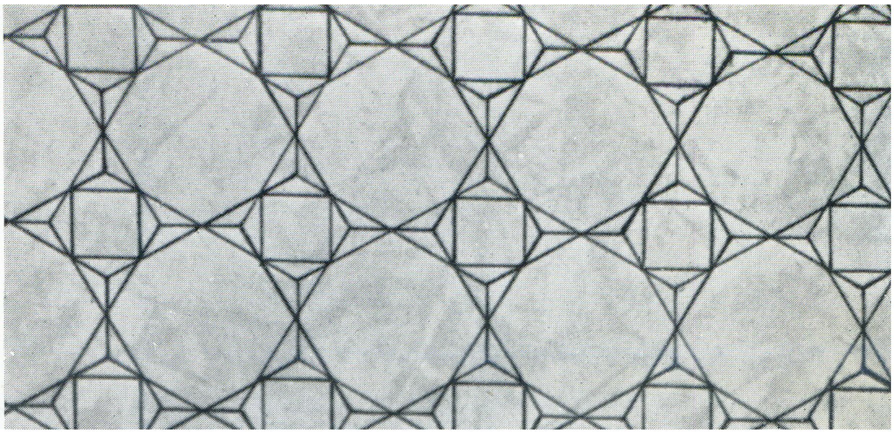

Figure 23 Image of Warerite plastic sheet pattern designed by Martin O. Rowlands for the FPG.

The examples in this section show that Megaw did not merely ‘supply’ diagrams to the group (as her contract stipulated). She was more than a passive channel between the scientific community and the group’s designers. Rather, Megaw’s diagrams exhibit her taste in certain aesthetic features: rotational symmetry, repeating pattern, geometric form and symmetry. In putting ‘more emphasis on their decorative aspects’, as Megaw described it in the quote at the beginning of this section, she acted as though she was beginning the process of translating the diagrams into pattern design herself.

Accuracy and the aesthetic diagram

The fact that Megaw was charged with upholding the accuracy of crystallographic diagrams in their transmission to pattern design may contribute to the fact that historians have not considered the possibility of her manipulation of diagrams toward decorative ends. The authors who have focused most on Megaw highlight the preservation of accuracy as a central preoccupation of hers[54]. Megaw was indeed concerned with preserving the scientific meaning of the diagrams in their translation to pattern design, but I contend that accuracy and the manipulations necessary to Megaw’s production of a ‘decorative’ diagram were not mutually exclusive. In fact, the very framework of scientific practice that conditioned many British crystallographers’ visualisation processes at the time afforded Megaw’s production of ‘decorative’ diagrams. There are two

[54] Jackson, *From Atoms to Patterns*; Forgan, ‘Festivals of Science’.

important points here: the first pertains to Megaw's working process and the second to the very notion of how much formal manipulation crystallographic diagrams permit.

Megaw's process of producing 'decorative' diagrams was nearly identical to the processes of crystallographic visualisation used in scientific work. As a doctoral student Megaw was trained by Bernal and spent most of her research career at Birkbeck and Cambridge. As such, she was embedded in the framework of mid-century X-ray crystallography visualisation practices described in chapter one as guided by the 'workmanship of risk': the kind of craft process described by David Pye in which the final form of a product is undetermined from the beginning and 'depends on the judgment, dexterity and care which the maker exercises as he works'[55].

Megaw's archive of working drawings shows that her process of developing diagrams for the FPG was such a craft process. It was marked by indeterminacy, as she experimented with possible compositions before alighting on a final diagram she preferred. Her drawings indicate that this was often a material process, reliant upon the physical manipulation of paper and its affordances, as in crystallographers' scientific work involving diagrams described in chapter one. Megaw's process of handling 'layers' of atoms in a given structure is an example. Because crystal structures repeat in three dimensions, when drawing a diagram one must contend with several layers of atoms at different elevations in the structure, which will appear superimposed upon one another in the two-dimensional diagram. In cases where Megaw worked from data for the positions of atoms in a molecular structure in composing a diagram for the FPG, she frequently sketched constituent layers of a structure as separate diagrams containing a few layers each (Figure 24). In several other cases she drew constituent layers on tracing paper, superimposed them and traced. For example, figures 25 and 26 show different groups of layers in an afwillite structure, which when superimposed form the basis of a dyeline Megaw submitted to the FPG (Figure 27). Drawing layers in the structure separately was part of Megaw's process of working out a diagram from data in the first place for many structures (as Forgan has also pointed out), but I argue

[55] Pye, p. 20.

that this process also afforded the aesthetic manipulation Megaw performed in her pursuit of ‘decorative’ diagrams[56].

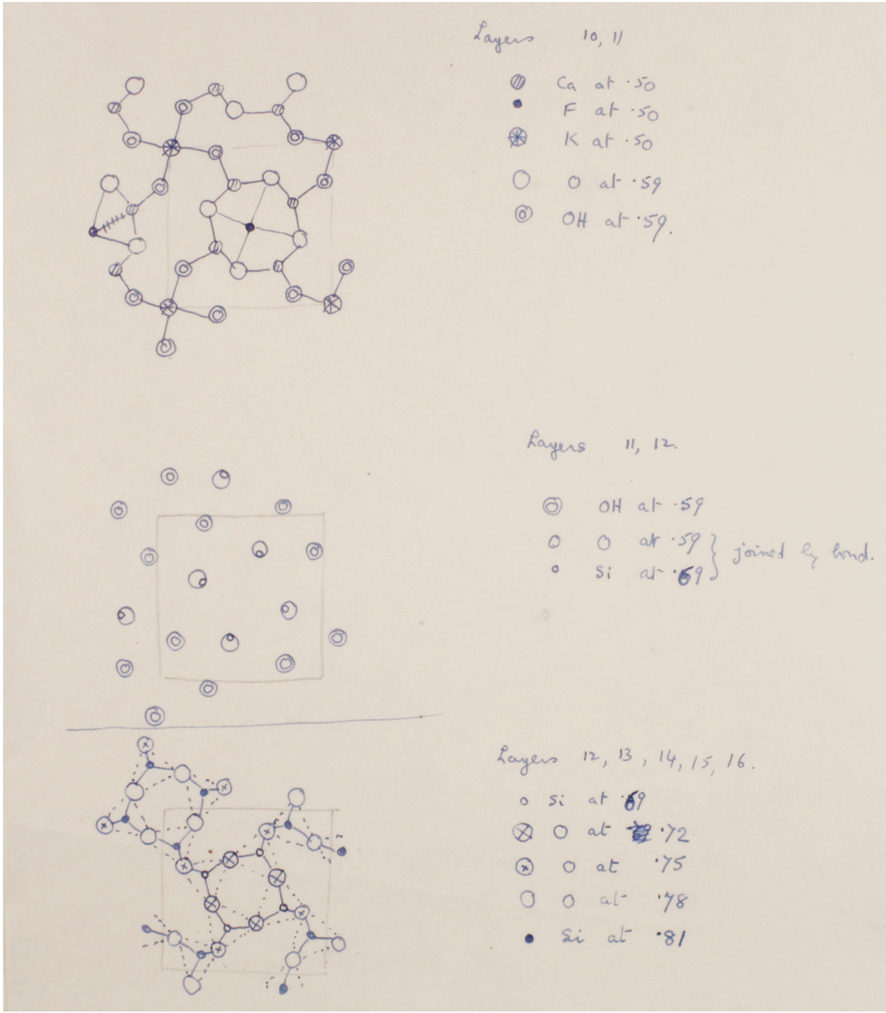

Figure 24 Megaw’s working drawing (for her FPG diagrams) of an apophyllite structure.

[56] Forgan, ‘Festivals of Science’.

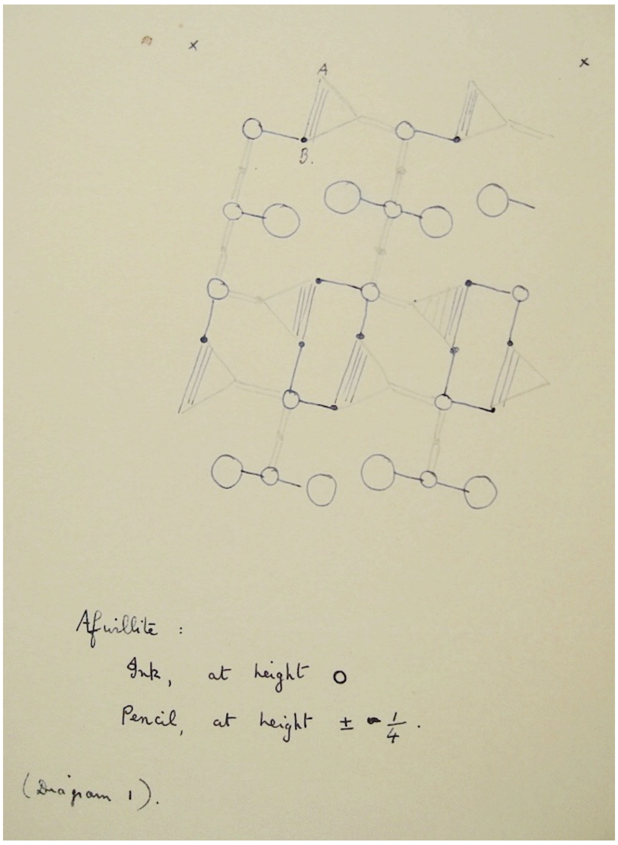

Figure 25 Working diagram of afwillite by Megaw marked ‘Diagram 1’.

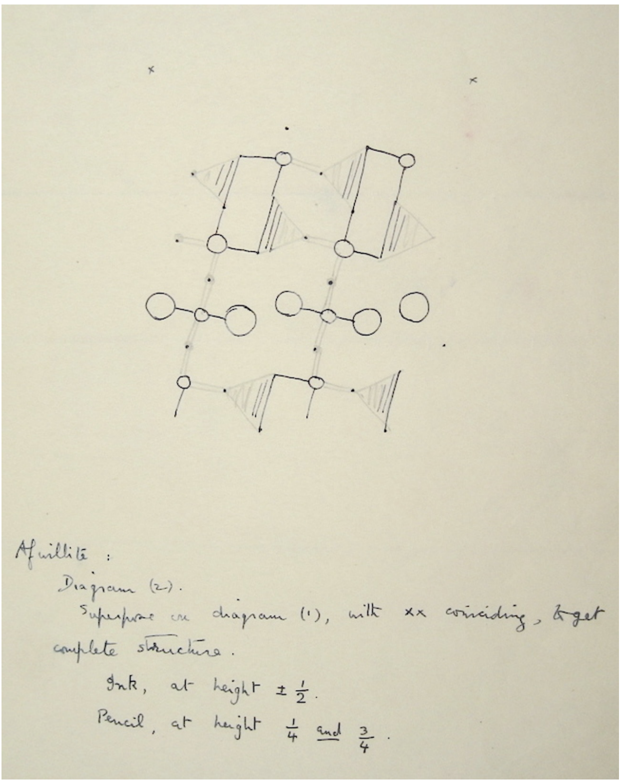

Figure 26 Working diagram of afwillite by Megaw marked ‘Diagram 2’.

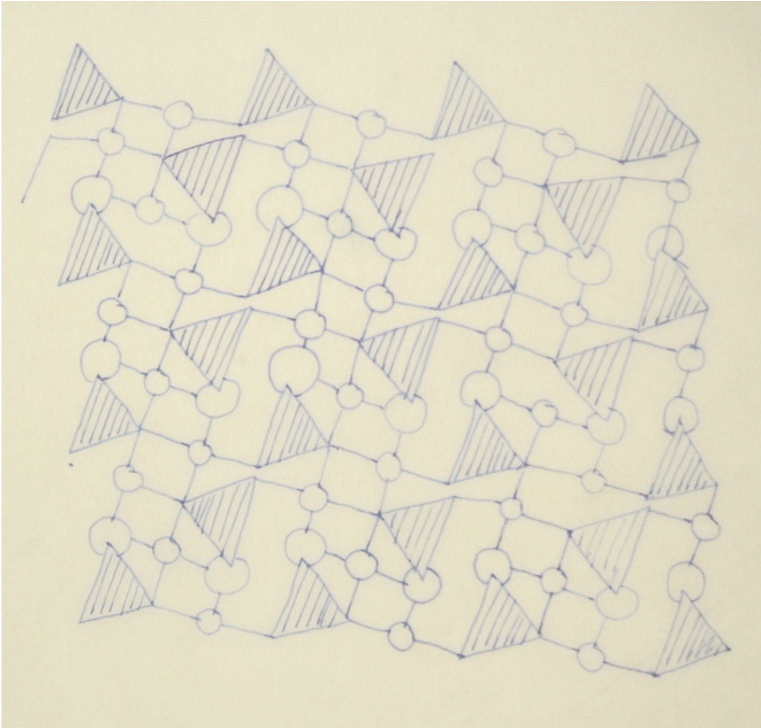

Figure 27 Working diagram of afwillite by Megaw, which is a tracing of Diagrams 1 and 2 (above) superimposed.

Drawing layers in a structure separately allowed Megaw to manipulate the appearance of a structure by selecting some layers in a structure and leaving out others. Constructing a structure from individual two-dimensional diagrams representing different layers as well as processes of shifting these superimposable diagrams around mimicked operations performed in crystallographic practices described in chapter one, such as work with electron density maps. In this case, instead of seeking patterns and structural comparisons with scientific interest, Megaw experimented aesthetically, working towards drawings that conformed to her taste in diagrams. For example, the final afwillite diagram combining several layers (Figure 27) displays the more continuous repeating pattern of joined-up constituent forms (much like Megaw's beryl diagram referenced earlier), which her diagrams indicate that she preferred, than do the working drawings with fewer layers represented (Figures 25 and 26). In other cases, although she produced several working diagrams of a given structure representing different combinations of layers at different heights, not all of these layers always appeared in the final diagrams submitted to the FPG. For example, in Megaw's working diagrams of apophyllite shown in Figure 24 the diagram at the top of the page includes layers not included in the diagram at the bottom of the page. This bottom diagram, which formed the basis for a diagram submitted to the FPG, appeals to a preference for geometric form more than it might if she had included the additional layer represented in the diagram at the top of the page, which contained atoms that would punctuate the geometric rings of oxygen atoms in the final diagram.

The affordances of tracing paper, the medium of many of Megaw's working drawings, were important; the paper itself could become a 'slice' of a molecular structure. This makes it possible to remove layers and recombine them almost as though manipulating the three-dimensional structure itself. Megaw worked toward 'decorative' diagrams much as a crystallographer might have worked towards the construction of a visualisation in the laboratory. She exercised the 'judgment' and 'dexterity' of the craftsperson operating within the 'workmanship of risk', with an eye out for just the right pattern.

Megaw's manipulations of diagrams for the FPG described so far do not preclude the production of a scientifically meaningful diagram. In fact, Megaw expressed this herself in notes distributed to the FPG outlining how diagrams might be mediated while still maintaining scientific accuracy:

> the same structure can be represented in a very large variety of ways, just as a map of England may show roads, or rivers, or counties, or mountains or a combination of several of these at once. It is legitimate to show only those features of the map which one desires to emphasise for a given purpose; but it is not legitimate to change their positions, or to put in things which are not there, or to put in some things of one kind and leave out others exactly similar. Colouring may be done in any way, providing things which are identical are coloured identically. A further choice concerns repetition of the pattern […] The limits can be drawn anywhere convenient, provided they enclose at least one repeat unit.[57]

In this text to designers Megaw specifies many of the same kinds of alterations that she made herself, and which I have identified in this section as processes through which she created 'decorative' diagrams. These include selecting certain information about a structure while leaving out other information (modulating the level of detail), selecting one convention over another, and extending the number of repeats included in a diagram. This shows

[57] Helen Megaw, 'Notes on Crystal Structure Diagrams', 12 January 1950. DCA 5396.

both that Megaw undertook operations that she expected to be part of the FPG's design process, and that these operations did not conflict with scientific practice.

There is much room for formal manoeuvring within what constitutes an 'accurate' representation. This should not be surprising to a historian of science. But this issue and its ramifications for the cultural transmission at the heart of the FPG have not been fully explored in the literature on this topic. This is in part because historians of design have written most accounts of the FPG, so an analysis of the diagrams produced by the group's scientist is not familiar territory disciplinarily.

The only author to broach the topic of Megaw's technical process of producing diagrams is Forgan, for whom, as a historian of science, Megaw's role in the FPG is a natural subject matter[58]. Comparison between normal crystallographic practice and Megaw's composition of FPG diagrams is not a component of Forgan's analysis and the possibility of Megaw acting in accordance with a conception of design does not arise in her account[59].

Conventionalised nature

Megaw's emphasis on repetition, symmetry, geometry and two-dimensionality in preparing diagrams for the FPG corresponds to the specific mode of practice in design drawing associated with the South Kensington system of design education. The name refers to the teaching methods implemented in the country's Schools of Design (and references the site of the main school in South Kensington, London, neighbouring the V&A). Their superintendents, design reformers Henry Cole, a civil servant and organiser of the 1851 Great Exhibition, and artist Richard Redgrave, placed central importance upon drawing as the basis

[58] In a brief description of some aspects of Megaw's process, Forgan observes that Megaw was 'experimenting with drawings of different crystal formations, discarding some as unsuitable and simplifying others'. Although she does not elaborate in detail, Forgan suggests that Megaw's 'was a complex process, embedded in scientific practice, though at the same time she was delighted by the beauty and symmetry of the patterns'. Forgan, 'Festivals of Science', p. 229.
[59] Forgan's discussion of Megaw's preparation of diagrams is not rooted in the contingencies of crystallographic visualisation practice, perspectives on the diagrams informed by studies of scientific representation or relevant sources on crystallographic visualisation outside of Megaw's own descriptions of crystallographic practice composed for members of the FPG.

of an education in 'practical art'[60]. Along with their associates in what came to be known as the 'South Kensington circle', these Victorian design reformers were impelled by a shared disappointment in British manufactures (which became especially apparent to them in the presentation of British products at the Great Exhibition). Worried about the 'degradation' of ornament at the hands of the machine, they aimed to modernise British design to suit the mechanisation of production well underway across numerous industries at the time[61].

In seeking new principles of design for industry, these design reformers valued mathematical principles underpinning architectural training at the time: geometric form and symmetry. Redgrave saw these as 'a necessary condition of repetition', an element favoured by their approach[62]. Figure 28 shows a pattern 'founded on combinations of the octagon' that Redgrave used to illustrate the principle of geometry 'as the basis of symmetry'[63]. (Its geometrical borders resemble the flattened solids in Megaw's apophyllite diagram in Figure 22.)

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[60] What became known as the South Kensington system was put in place following the Board of Trade's establishment of its Department of Practical Art in 1852, headed by Cole and Redgrave (it was renamed Department of Science and Art the following year). The names reflected the utilitarian outlook of this endeavor, which saw design education serving the needs of manufacturing, and a view held by the school's superintendents that design, based in principles of geometry and Utilitarian values, was continuous with science. Further background on this subject can be found in Stuart Macdonald, *The History and Philosophy of Art Education* (Cambridge: Lutterworth, 2004); Christopher Frayling, *The Royal College of Art: One Hundred and Fifty Years of Art & Design* (London: Barrie & Jenkins, 1987); David Brett, 'Drawing and the Ideology of Industrialization', *Design Issues*, 3 (2) (1986), 59-72; Quentin Bell, *The Schools of Design* (London: Routledge and Kegan Paul, 1963).

[61] In his 1852 post-mortem on the Great Exhibition, Redgrave wrote that where 'ornament is wholly effected by machinery, it is certainly the most degraded in style and execution [...] this partly arises from the facilities which machinery gives to the manufacturer, enabling him to produce the florid and overloaded as cheaply as the simple forms, and thus to satisfy the larger market for the multitude, who desire quantity rather than quality, and value a thing the more, the more it is ornamented'. Richard Redgrave, *Report on Design* (London: William Clowes and Sons, 1852), p. 8.

[62] Richard Redgrave, *A Manual of Design* (London: Chapman and Hall, 1876), p. 139.

[63] Ibid, p. 141, 140.

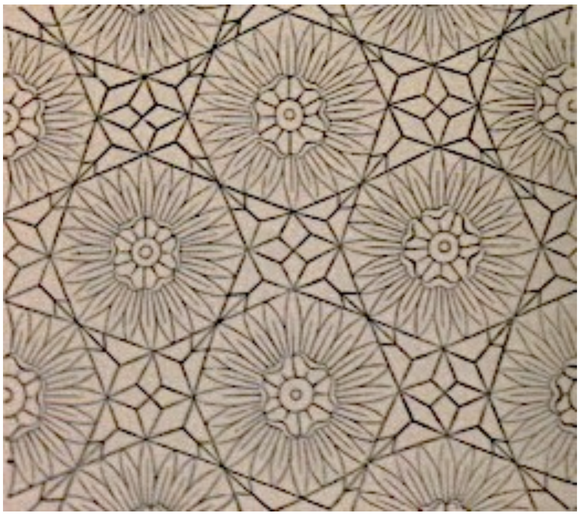

Figure 28 Figure included in Redgrave's *A Manual of Design*.

Platonic ideals were elevated to *laws* of design; the straight line, the curved line, and models of geometrical solids copied by pupils were fundamental[64]. *The Grammar of Ornament* (1856), a pattern sourcebook by a member of this circle, interior designer Owen Jones, embodies the South Kensington circle's zeal for geometric principles - and their urge to codify[65]. Jones put forth compositional principles for ornamental design based upon architectural principles, and looked to examples outside Western European traditions (as did his compatriots), with distinct praise reserved for the geometrical repeating patterns found in the Alhambra (Figure 29).

[64] Brett, 'Drawing and the Ideology of Industrialization'.
[65] Owen Jones, *The Grammar of Ornament* (London: Dorling Kindersley, 2001 [1856]).

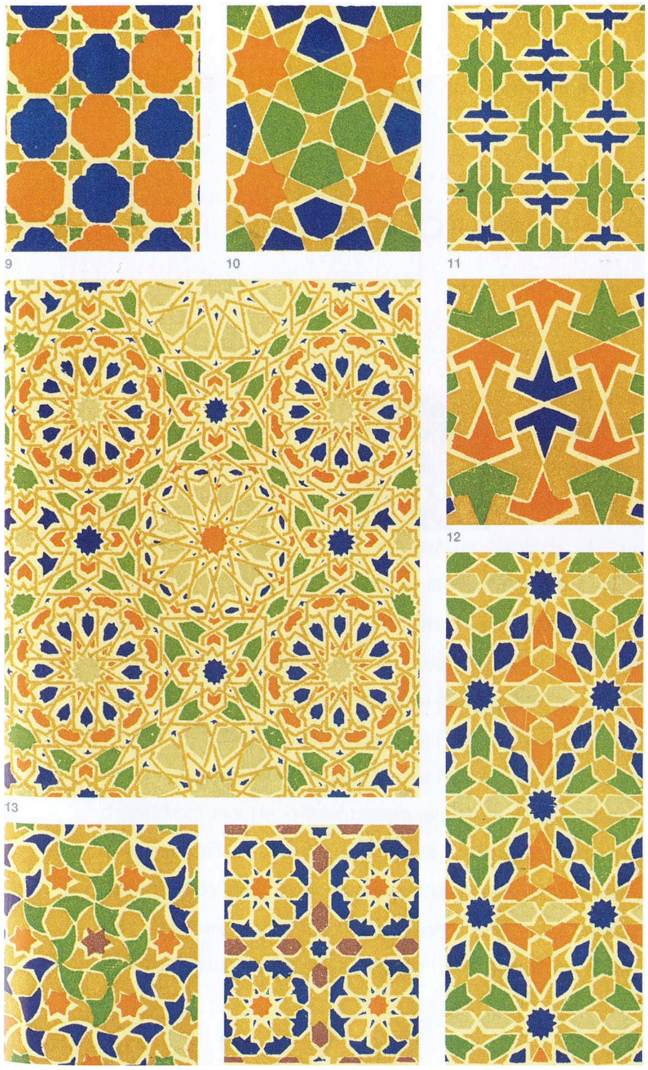

Figure 29 Images based on mosaics from the Alhambra pictured in Jones' *The Grammar of Ornament*.

The South Kensington system became synonymous with the 'conventional' style of rendering nature, or the abstraction of natural, usually botanical, forms through their formatting as flat geometric motifs, which were then repeated to create ornamental compositions suitable to machine production. The pattern by the designer Christopher Dresser of the South Kensington circle in Figure 30 is an example. This codification of ornamental draughting served also, as Redgrave wrote, 'a language of accurate description'[66]. It was to ease communication between designer and producer, roles by then seldom performed

[66] Redgrave quoted in Frayling, *The Royal College of Art*, p. 42.

by the same individual, given the industrialisation of the production of patterned products such as textiles and wallpaper[67].

Figure 30 Pattern by Christopher Dresser showing the abstraction of botanical forms into repeated geometrical motifs that was typical of the South Kensington style.

A positivistic 'scientism' underpinned this philosophy of drawing: 'accurate description' could be attained through recourse to fundamental geometries perceived in botanical forms[68]. In his book *A Century of Painters*, Redgrave describes his method of extracting pattern from the diagrammatic rendering of plants:

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[67] For instance, machine-printed wallpapers were first sold in England in 1841. Joanna Banham, 'The English Response: Mechanization and Design Reform', in *The Papered Wall*, pp. 132-149.

[68] Brett, *Rethinking Decoration*, p. 114. Science was in fact part of the curriculum, as 'Art-botany', which comprised scientific lectures on plant structure for design students (p. 109).

> It consisted first in the ornamental analysis of plants and flowers, displaying each part separately according to its normal law of growth, not as viewed perspectively, but diagrammatically flat to the eye[69].

Another convention of the South Kensington style was the production of a natural motif within a defined geometrical area. A training task for the 'Elementary Design' stage involved composing 'Ornamental arrangements to fill given spaces in outline, monochrome, or modelled'[70]. Redgrave devised such an exercise involving fitting 'Flowers and leaves of wild strawberry within a pentagon' using specified elements of the plant[71]. Figure 31 shows an example of such a composition, from an instructional drawing text by Walter Smith, Head Master of the Leeds School of Art, and a South Kensington school graduate, who taught its methods[72].

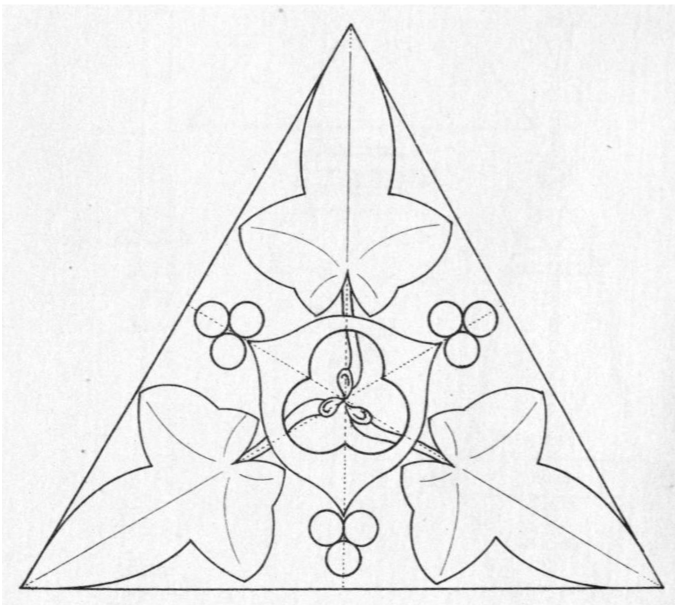

Figure 31 Example ornamental composition from an instructional drawing book by Walter Smith (c.1860s/1870s).

This approach replaced a method of design education privileging the copying of existing examples, and represented a reaction against naturalistic

[69] Richard Redgrave and Samuel Redgrave, *A Century of Painters* (London: Smith Elder, 1866), p. 564-5 cited in Macdonald, *The History and Philosophy of Art Education*, p. 237-8.
[70] *Syllabuses of Third Grade Exams* (London: Science and Art Department, 1889).
[71] Richard Redgrave, *Directory* (London: Science and Art Department, 1856-7), cited in Macdonald, *The History and Philosophy of Art Education*, p. 238.
[72] Brett, 'Drawing and the Ideology of Industrialization'.

ornamentation produced at the time, which was championed by the art critic John Ruskin. Naturalistic ornament involved illusions of three-dimensionality – eschewed by the South Kensington style - in the representation of natural forms (this style is exemplified by the pattern for a carpet shown at the 1851 Great Exhibition in Figure 32).

Figure 32 Carpet design representing a naturalistic style (the plants maintain an illusion of depth) by E.T. Parris for Turberville Smith & Co, shown at the 1851 Great Exhibition.

The South Kensington method of drawing, which involved 'flattening', natural forms, making them symmetrical and geometrical, and then repeating them, bears clear coherences with Megaw's method of sketching diagrams for the FPG. There are indeed pre-existing coherences between some crystallographic conventions and the South Kensington tradition's 'conventionalised nature'; the latter is after all motivated by a notion of 'scientific' precision, and, conversely, many crystal structures lend themselves to geometrical rendering. But certainly not all crystallographic diagrams produced in this period resembled these ornamental conventions as Megaw's diagrams for the FPG do[73]. Aligning the crystallographic diagram with these design drawing conventions meant emphasising specific features over others and making formal decisions such as excluding isometric perspective diagrams and repeating the unit cell extensively, which were unusual in crystallographic practice.

A further example of the parallels between Megaw's FPG diagrams and the South Kensington method is found in an instance in which Megaw produced a diagram resembling a geometrically conventionalised floral pattern, echoing the South Kensington system's conventionalised botanical ornament. Megaw submitted three drawings of lithium chlorate trihydrate on a single page, writing that they 'differ only in style of drawing' (Figure 33)[74]. The diagram at the bottom of the page shows circular 'atoms' darkened and foregrounded such that they are more prominent than the straight lines linking them, resulting in rings of circles that create a botanical form or a rosette, a conventionalised decorative floral relief used in architecture (in fact copying rosettes was a component of some South Kensington drawing exercises[75]).

[73] As mentioned earlier, many electron density maps and Patterson diagrams as published by crystallographers do not, diagrams drawn in three-dimensional projection do not, and scientists rarely extended a diagram to include several repeats.
[74] 'Dr. Megaw's Notes on Crystal Structure Diagrams'.
[75] MacDonald, *The History and Philosophy of Art Education*. A book of lectures given in the Science and Art Department describes rosettes as the 'proper development into pure ornament' of 'floral and leaf growth': 'The results, obtained by grouping a cluster of leaves together in this manner, are finer and stronger in appearance than any imitation of flowers'. James Ward, *The Principles of Ornament*, ed. by George Aitchison (London: Chapman and Hall, 1899), pp. 108-109.

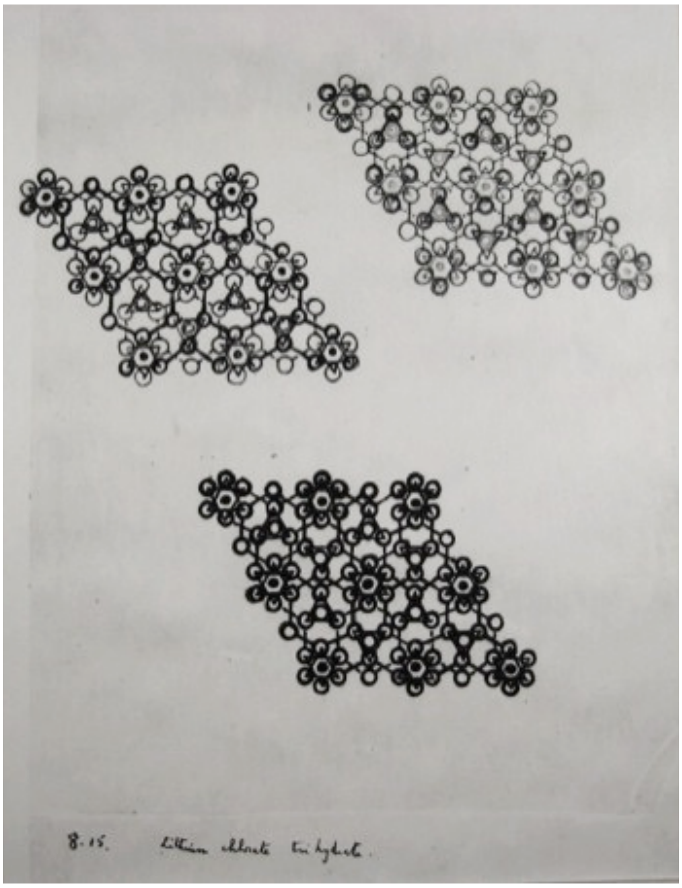

Figure 33 Megaw's working drawing of a lithium chlorate trihydrate for the FPG.

There is evidence that Megaw's early education was at the root of the fact that her drawings align with the South Kensington approach to ornamental design. Redgrave had developed a version of this method of design education for primary schools throughout Britain, and it persisted into the early decades of the twentieth century[76]. The general context of design education had changed by this time, being eclipsed somewhat by a focus on fine art rather than training for industry as in Redgrave's period[77]. However, Megaw studied 'Design Drawing' when she was in school in Northern Ireland at this time and her curriculum bore the marks of the South Kensington method[78].

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[76] Frayling, *The Royal College of Art*, p. 41.

[77] Stuart MacDonald, 'Articidal Tendencies', in *Histories of Art and Design Education*, ed. by David Thistlewood (Harlow: Longman Group, 1992), pp. 14-22.

[78] MacDonald points out that art education in schools at this time consisted largely in instruction in different types of drawing including 'object drawing, memory drawing, geometrical and mechanical drawing' in addition to the drawing-heavy ''Design', which consisted of space-filling, drawing out patterns, and occasionally modeling motifs in clay'. MacDonald, *The History and Philosophy of Art Education*, p. 309.

This is evident from Megaw's intermediate examination booklet in 'Drawing (Design)' from 1921 (when she was 14), held in her Girton College archive. It instructs pupils to draw a triangle within which to 'make a design to fill the space' using specific elements of a tulip as pictured (Figure 34). This brief replicates the South Kensington exercise described above in which an ornamental composition must be drawn inside a 'geometric figure'. The example in Megaw's exam booklet (Figure 35) echoes similar examples from South Kensington drawing exercises for the 'Elementary Design' stage mentioned earlier, which involved composing 'Ornamental arrangements to fill given spaces' (Figure 31)[79]. Megaw's preliminary draft sketch, preserved in the archive, sees the then-14-year-old Megaw attempting to confine the constituent elements of a tulip into a triangle (the archive does not include her actual exam submission) (Figure 36).

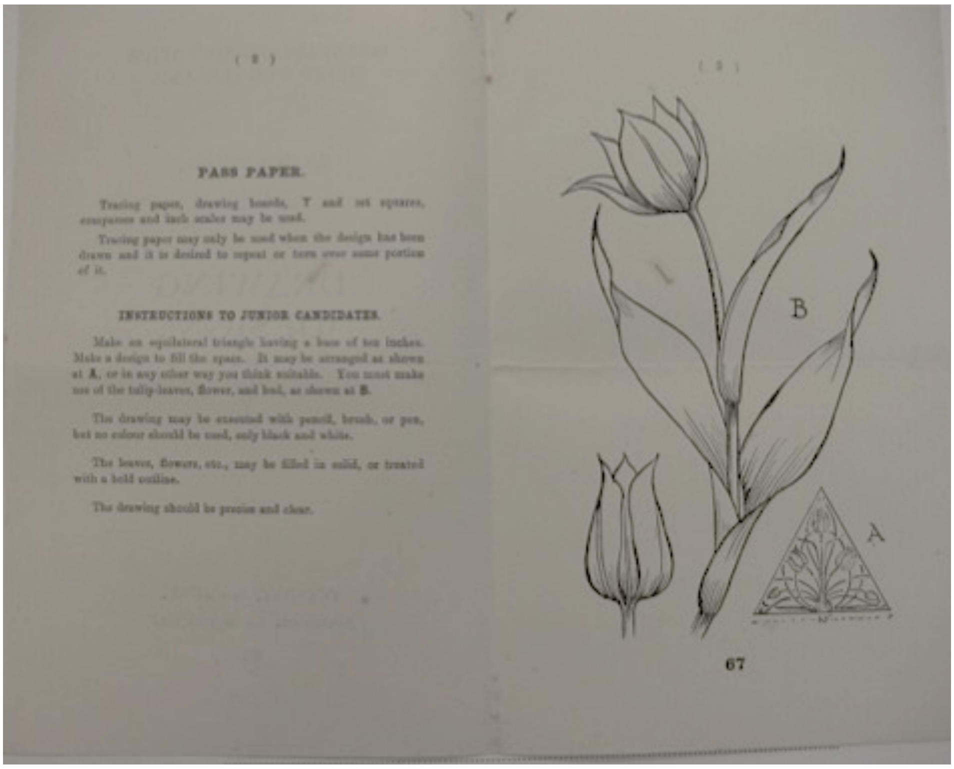

Figure 34 Helen Megaw's 1921 examination book for 'Drawing (Design)'.

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[79] *Syllabuses of Third Grade Exams* (London: Science and Art Department, 1889).

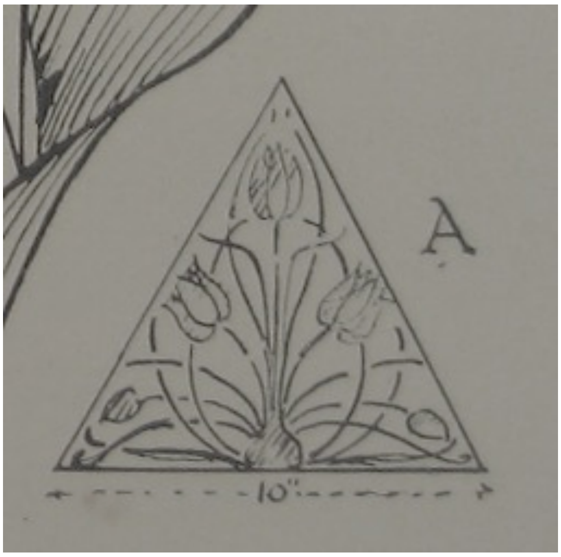

Figure 35 Detail from Helen Megaw's 1921 examination book for 'Drawing (Design)', pictured above.

Figure 36 Draft sketch by Megaw for her 1921 examination in 'Drawing (Design)'.

The above analyses indicate that in the FPG's transmission of scientific material to pattern design, Megaw was not only the source of material to be translated; she participated in its translation. She mediated the FPG's diagrams in accordance with particular design conventions: those associated with the South Kensington approach, which had impacted her early training in design drawing. The features of ornamental composition typical of the South Kensington style correspond to Megaw's judgment of a sufficiently 'attractive' and 'decorative' diagram. In this way, Megaw's educational background inflected her taste in diagrams, which guided her work for the FPG.

Victorian taste and crystallographic diagrams

Megaw's taste in diagrams explored here evidences reference points in Victorian decorative art. In addition to the resonance of her production of diagrams with the Victorian mode of design drawing explored above, Megaw further indicated the Victorian reference points for her taste in decoration in a 1946 letter to the DRU's director Marcus Brumwell, discussing her proposal. She mentions the nineteenth-century Arts and Crafts designer William Morris, known for his wallpaper patterns based on repeated motifs drawn from nature. She suggested that textiles with patterns derived from crystallography diagrams should be named after the substance represented in a given diagram 'just as the William Morris patterns were called after their constituent flowers', revealing the Victorian designer as a reference point[80].

Megaw was not the only British crystallographer in this period whose taste in Victorian decorative art inflected their reflections on the aesthetics of crystal structures. As the literary scholar Suzanne Black's study of W.L. Bragg's writings indicates, when explaining crystallographic concepts in terms of designed objects such as wallpapers, 'Bragg's explicit frame of reference is the Victorian decorative arts'[81]. Illustrations and comments in Bragg's writings reflect the influence of Arts and Crafts designer Walter Crane's *Line and Form*, a handbook for producing designs in accordance with the naturalistic school of Victorian ornamental design led by Ruskin[82]. Bragg published Crane's pattern designs as illustrations of crystallographic concepts in his book *The Crystalline State* (1933). In 1975's *The Development of X-ray Analysis*, he reiterated Crane's position that lack of detail distracting from the bare visual fact of the continuous repeat makes for a 'dull' pattern[83].

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[80] Helen Megaw to Marcus Brumwell, 20 February 1946. AAD 1977/3/12.
[81] Black, 'Domesticating the Crystal', p. 272.
[82] Walter Crane, *Line and Form* (London: George Bell & Sons, 1902).
[83] Black, 'Domesticating the Crystal', p. 270. Bragg, *The Development of X-Ray Analysis*; Bragg, *The Crystalline State*.

For both Megaw and Bragg, the Victorian taste they exhibit decades into the twentieth century may speak to their class background. Both came from upper-middle-class intellectual families: Bragg, as the son of a physicist, and Megaw, daughter of a judge in the Northern Ireland High Court and Member of Parliament. Historian of the Cavendish J.G. Crowther described Bragg's background,

> born in a cultivated and comfortable atmosphere, […] with good social and educational facilities. He was gifted, but he was also freed from common obstacles. His mind was formed in the Victorian and Edwardian periods[84].

Even in the 1930s, British intellectuals were by and large resistant to the modernist domestic design emanating from continental Europe, and the prewar period even saw a Victorian revival among middle-class consumers[85]. Although Megaw was 17 years younger than Bragg, she would have easily been exposed to a taste in Victorian decorative styles not only through the continued resonance of the South Kensington system in her schooling, but also through her upbringing.

Megaw's exposure to Bragg's taste through her scientific training and career is a further possible social factor conditioning Megaw's taste and her application of her criteria for decorative art to diagrams. W.L. Bragg was director of the Cavendish in 1946 when Megaw moved to the laboratory as a researcher. Additionally, Megaw was a research student in 1933 when *The Crystalline State*, in which Bragg reproduced Crane's designs, was published (she finished her PhD in 1934), and like many young and aspiring crystallographers at the time, she probably read it. She was clearly aware of Bragg's use of pattern design as an analogy for crystal structure; Megaw's 'Pattern in crystallography' essay references a 1940 Royal Institution lecture in which he presented numerous fabrics that represented different forms of symmetry[86]. Megaw's original proposal to the DRU, which highlighted textiles and wallpapers, suggests Bragg's influence.

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[84] Crowther, p. 311.
[85] Deborah Cohen, *Household Gods: The British and Their Possessions* (New Haven and London: Yale University, 2006).
[86] Megaw, 'Pattern in Crystallography'.

This study of the FPG thus reveals multidirectional flows between design and science. Most literature touching on transmissions between these fields focuses on trajectories of transmission or influence from science to design. But Bragg and Megaw show evidence of transmission in the other direction. And in Megaw's case, this affected her work for the FPG through her incorporation of non-scientific aesthetic frameworks into the production of diagrams.

Megaw's hybrid practice

Megaw clearly intended to format her diagrams for the FPG as decorative objects, but I do not claim that Megaw proceeded consciously in the deployment of conventions associated with the South Kensington method. Choices and behaviour guided by taste are not necessarily conscious or explicitly articulated, and this is the case with Megaw's production of FPG diagrams. Megaw was, after all, not a professional designer. Instead, as I demonstrated earlier, Megaw undertook her process of producing 'decorative' diagrams within the framework of crystallographic visualisation practice.

Megaw's diagrams for the FPG reveal a subtle balancing act between the frameworks of scientific practice and the pursuit of goals typically located outside it: Megaw used the tools honed in her scientific practice to *manoeuvre* diagrams into accordance with her vision of decorative art. Historian of science Jenny Bangham describes 'manoeuvrability' as one of the syntactical elements of the scientist's 'paper tools' that serves knowledge generation, referring to genetics researchers' use of systems of nomenclature for 'doing experiments on paper'[87]. The word 'manoeuvre' suggests not only manipulation or movement, but also strategic movement, and this sense of the term is relevant in the arena of scientific diagrams as well. Scientific visualisations are never neutral; by an advanced stage in the research process, if the research is useful or meaningful at all, visualisations usually indicate a position on a given research question and/or wider debate within the field. Latour has made this point most forcefully, deploying numerous military metaphors to emphasise the role of what he terms 'inscriptions' in scientific debate. Even though they are rarely textual, inscriptions 'bear on certain controversies and force dissenters into believing

[87] Bangham, 'Writing, Printing, Speaking', p. 336, 339.

new facts and behaving in new ways', he writes[88]. Given these conditions under which visualisations are normally used in scientific practice, it would have been difficult in fact for Megaw to produce diagrams *without* a specific aim in mind. Only in this case, her aim was the production of an aesthetically 'good' pattern.

This echoes Kaiser's recent research on the varied postwar use of Feynman diagrams across geographically disparate communities of physicists, whose transmissions and re-translations of the diagrams indicated how 'plastic' the diagrams were, as they were turned to different uses according to the interests of a given local context[89]. The crystallographic diagram was similarly plastic in Megaw's hands as she anticipated their arrival in a new context. In this case, however, rather than tracing the movement of diagrams through scientific communities, we see the diagram modulated to slip quietly out the doors of the laboratory altogether, transmitted into a different domain: design.

In drawing diagrams that were both scientific and decorative, Megaw thus created a hybrid, or what literary theorist Mikhail Bahktin described as 'two social languages within the limits of a single utterance'[90]. Megaw's aim in producing diagrams for the FPG straddled scientific accuracy and - in her judgment - decorative appeal. In one language, the conventions of crystallographic visualization, she was fluent, an expert. In the other, that of design drawing, she was not a professional, but was confident to follow her taste as a guide (just how these 'decorative' diagrams were received by professionals in the postwar design community will be discussed in the following sections).

Megaw's production of hybrid diagrams/patterns prompts reflections on the issue of cultural transmission and translation. It problematises the way many design histories engage with 'science' as a source for design: as a passive source and as an impregnable entity. In terms of the issue of cultural transmission in the FPG, the fact that the FPG's scientific source material was already mediated - and in line with a specific framework of design drawing - challenges the existing model of cultural transmission from science to design sketched by other authors on the FPG. Firstly, it shows that the FPG story is not only characterised by

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[88] Latour, 'Drawing Things Together', p. 25.
[89] Kaiser, p. 174.
[90] Mikhail Bahktin, 'Discourse in the Novel', in *The Dialogic Imagination*, by Mikhail Bahktin, ed. by Michael Holquist, trans. by Caryl Emerson and Michael Holquist (Austin: University of Texas, 1981 [1935]), pp. 269-422 (p. 358).

transmissions of science to design, but by the movement of knowledge and practices in the other direction as well. Megaw's diagrams evidence transmission from design to science through the visible effects of design drawing methods on the work of a scientist (and approaches to crystallographic patterns effected by ideas from the Victorian decorative arts).

Secondly, this expands the view of the project's aesthetic cultural translation beyond the work of the professional designers. Scholars have not entertained the notion that Megaw mediated the diagrams circulated to the FPG in accordance with any conventions of pattern design – nor does her own design education figure into any scholarship[91]. Historians do not *expect* Megaw to have acted in any way beyond her remit as a scientist. This is perhaps due to the fact that the FPG has been viewed primarily from a design history perspective. Examining Megaw's FPG diagrams for traces of design drawing technique or proclivity toward ornamental styles requires familiarity with both crystallographic drawing practices and those of design. As a boundary-crosser, Megaw resists the disciplinarily-defined frameworks within which most historical scholarship operates.

I return now to the concept of the network introduced at the beginning of the chapter. Megaw is one part of a larger network traced in this chapter, involving people and diagrams acting on one another. But there is also a sense in which a network of factors is perceivable within Megaw's work for the FPG itself. These include Megaw's taste in 'decorative' diagrams, shaped in part by her educational background, as well as frameworks of crystallographic visualisation practice at this time. These literally acted on her body, guiding her hand. On this concept of the network, Law writes,

> thinking, acting, writing, loving, earning - all the attributes that we normally ascribe to human beings, are generated in networks that pass

[91] Jackson's *From Atoms to Patterns* contains an index of the corresponding published source diagrams (ones that appeared in scientific journals or books) alongside Megaw's dyelines but makes no indication that there are significant differences between them. Jackson comments that Megaw's diagrams 'relate very closely to – or are exact reproductions of – published diagrams' (p.16).

> through and ramify both within and beyond the body. Hence the term, actor-network - an actor is also, always, a network.[92]

Actors do not only act upon things; forces, ideologies and interests operate upon actors (Latour defines the actor as 'what is *made to* act by many others'[93]). These are important to Megaw's place in the network I am tracing, and we will see the reverberations of the way she mediated diagrams as they circulate among other communities of practice in which different aesthetic frameworks and interests operated.

2. Crystal structure sympathisers

The meaning of Megaw's crystallographic diagrams shifted as they circulated in new contexts, encountering actors in fields outside of her own. In this section I describe the responses to and mediation of the diagrams by actors involved in the germination of the FPG who participated within various strands of modernism in architecture, fine art and design operating in postwar Britain. I will argue that examining the significance of crystallographic diagrams in these circles reveals the roots of the FPG's aesthetic mission in these specific modernist ideologies and aesthetic frameworks. In addition to illuminating the conditions of the FPG's cultural transmission between crystallography and design, this analysis sheds light on the place of scientific knowledge in postwar British design circles. I begin with Hartland Thomas, who organised the FPG.

Mark Hartland Thomas' crystalline aesthetic

Born in 1905, Hartland Thomas trained in architecture at the Royal West of England Academy in Bristol after studying classics at Cambridge. In 1932, he joined the practice of his father, Bristol's Diocesan Surveyor. He practised as an architect before the war, but mostly participated in the profession through leadership and organisation roles. Hartland Thomas's interests extended also to

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[92] Law, 'Notes on the Theory of the Actor-Network', p. 384.
[93] Latour, *Reassembling the Social*, p. 46.

industrial design, where he participated in policy planning and coordination as the CoID's Chief Industrial Officer from 1947 to 1951[94].

Hartland Thomas's enthusiasm for the use of crystallographic diagrams as the basis of pattern design was crucial to the FPG's emergence and his subsequent time-consuming management of it. He was interested in Megaw's prepared diagrams upon seeing them during Lonsdale's 1949 Society of Industrial Artists (SIA) talk, as his enthusiastic 1949 letter to Megaw (quoted earlier) written following the event indicates. The interests and the aesthetic ideologies governing his activities, which might have motivated his work with the FPG, however, have not been previously explored (in the historiography he simply represents the CoID). In this section, I argue that Hartland Thomas had very strong aesthetic convictions of his own that primed him to see potential in Megaw's diagrams.

Hartland Thomas's background as an architect is central to the roots of his interest in Megaw's diagrams. Therefore it is necessary to introduce his particular position within postwar British architecture. Hartland Thomas displayed a commitment to tenets of the modern movement in architecture. A 1936 survey of modernist homes by architect F.R.S. Yorke in the *Architectural Review* featured one of the few houses Hartland Thomas designed (Figure 37). He was an active member of the MARS group (Modern Architectural Research), the British arm of the Congrès internationaux d'architecture moderne (CIAM), which was associated with continental modernism[95]. Hartland Thomas organised the first postwar CIAM congress in Somerset in 1947[96].

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[94] Christine Wall, *An Architecture of Parts: Architects, Building Workers and Industrialisation in Britain 1940-1970* (London: Routledge, 2013).
[95] On MARS see John R. Gold, *The Practice of Modernism, Modern Architects and Urban Transformation, 1954 - 1972* (London: Taylor & Francis, 2007); Eric Paul Mumford, *The CIAM Discourse on Urbanism, 1928-1960* (Cambridge: MIT Press, 2000).
[96] 'Mark Hartland Thomas' [obituary], *Architectural Design*, August 1973, 544.

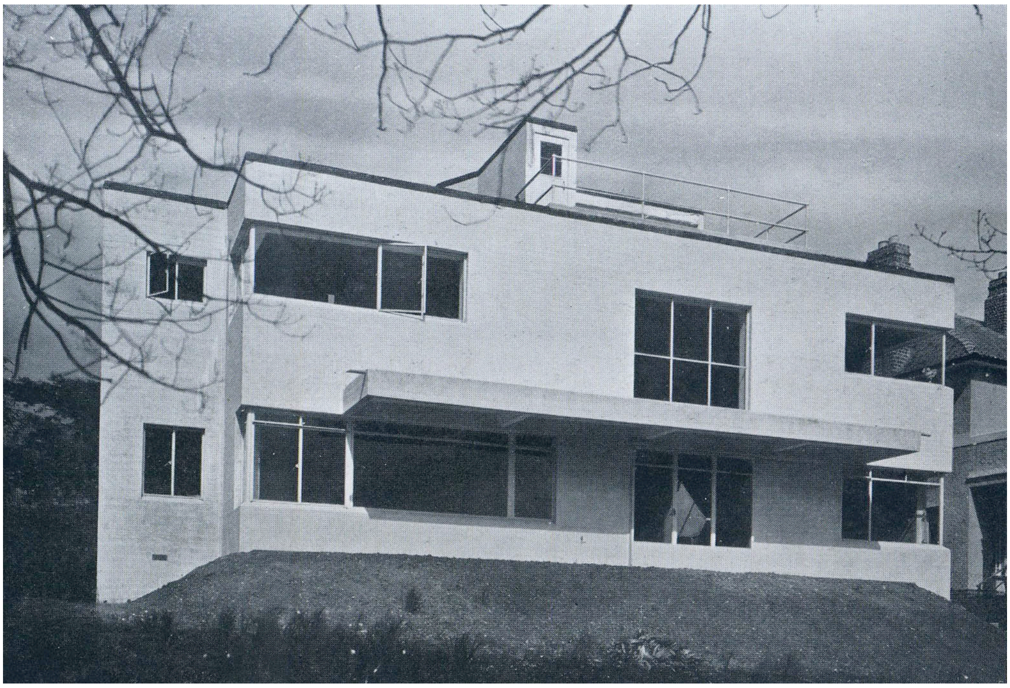

Figure 37 Hartland Thomas' 1935 'House at Sneyd Park, Bristol'.

Hartland Thomas was part of a British modernist architecture community facing dramatic changes after the war. As has been well-documented in the historiography, modernism in British architecture was, before the war, the purview of a small avant-garde[97]. But the postwar situation was different, as features aligned with continental modernism marked British architects' responses to new postwar conditions, affecting the status and expression of modernist values.

An important factor was state intervention in planning and building in response to postwar housing shortages. These measures were among the postwar Labour government's efforts to improve postwar social and economic conditions (alongside the nationalisation of several industries and the establishment of the National Health Service and National Insurance)[98]. The 1944 Housing Act

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[97] Mark Crinson and Claire Zimmerman, *Neo-Avant-Garde and Postmodern: Postwar Architecture in Britain and Beyond* (New Haven: Yale University Press, 2010); Nicholas Bullock, *Building the Post-War World: Modern Architecture and Reconstruction in Britain* (London: Routledge, 2002); Jeremiah. Compared to continental Europe, modernist architecture appeared relatively late in Britain, with work of modernist firm Isokon, established in 1929, and Georgian émigré architect Berthold Lubetkin's designs of the 1930s such as the Finsbury Health Centre in London, an open plan building with a front wall of glass bricks affording the flow of sunlight and air associated with continental modernist architecture.

[98] Alison Ravetz, *Council Housing and Culture: The History of a Social Experiment* (London: Routledge, 2001); Kenneth O. Morgan, *Britain Since 1945: The People's Peace* (Oxford: Oxford University Press, 2001).

committed £150 million to building temporary housing. And a 1945 White Paper on Housing projected the construction of 200 000 new homes in the coming years[99].

Seeking cheap and quick ways to build homes, policymakers looked to new, non-traditional methods of construction such as prefabricated housing. This resulted in an industrialisation of architecture: the implementation of methods for building and planning that aimed at greater efficiency in the use of materials and labour[100]. Such measures echoed continental modernism's theoretical principles promoting standardisation, but as a practical response to housing needs[101].

Some British architects saw industrialisation, Christine Wall writes, 'as an unjustifiable intrusion into the freedom of the designer'[102]. While some resisted these developments, others clamored to secure the architect's role in this new state of affairs. Eva-Marie Neumann analyses one such 'intense but short-lived' response: a devotion to proportion[103]. This marked a revived interest in the deployment of classical geometrical order in architectural design methods, which had antecedents in theories of continental modernist architecture, most closely identified with Le Corbusier[104]. It also evidences the legacy of the neoclassical Beaux-Arts tradition in architectural education in Britain that was still alive in the period when many postwar architects, including Hartland Thomas, were trained[105]. This targeted anxieties about the authorial role of the architect and

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[99] Bullock, *Building the Post-War World*; Barry Cullingworth and Vincent Nadin, *Town and Country Planning in the UK* (London: Routledge 2002); Brian Finnimore, *Houses From the Factory: System Building and the Welfare State* (London: Rivers Oram Press, 1989).
[100] On state-commissioned building, planning systems and the industrialisation of architecture in the postwar reconstruction of Britain see Nicholas Bullock, 'West Ham and the Welfare State 1945-1970', in *Architecture and the Welfare State*, ed. by Mark Swenarton, Tom Avermaete and Dirk van de Heuvel (Oxon: Routledge, 2015), pp. 93- 110; Wall; Finnimore.
[101] Finnimore, p. 3.
[102] Wall, p. 26.
[103] Eva-Marie Neumann, 'Architectural Proportion in Britain 1945-1957', *Architectural History*, 39 (1996), 197-221 (p. 197).
[104] Le Corbusier had used *tracés régulateurs* ('regulating lines') based on the Golden Section as a design tool as early as 1917. In the early 1950s his *Modulor* promoted human proportions (from which he derived a Fibonacci series) to be 'applied on a mass scale in the dimensioning of manufactured articles'. The book influenced postwar British architects preoccupied with proportion in design. Kenneth Frampton, *Le Corbusier* (London: Thames & Hudson, 2001), p. 19; Le Corbusier, *The Modulor*, trans. by Peter de Francia and Anna Bostock (Faber and Faber, 1954 [1950]), p. 62.
[105] A Bauhaus-inspired modernist approach took over from the Beaux-Arts tradition in British architectural education the 1930s. Reyner Banham describes the 'young generation of postwar architects' having 'passed through some form of rundown Beaux-Arts training', and 'all had had their interest in classicism confirmed by their readings in Le Corbusier'. Reyner Banham, *The*

associated concerns that the character of the profession as an aesthetic endeavor was threatened by what some architects saw as industrialisation's 'dehumanising effects', but in a way that compromised with the prevailing enthusiasm exhibited in modernist technocratic state planning for rationalised, 'scientific' techniques[106].

A rallying call to take up the commitment to proportion came from Hartland Thomas himself in 1947. Writing in *Architectural Design* that year he called for an 'architectural renaissance':

> During recent years architectural development has taken the form of rational planning and economy of means and these techniques are widely accepted. But in themselves they are not enough – they form the basis of a firm and necessary foundation of functionalism […] An aesthetic must be developed, worthy of these foundations, and architecture […] must again become an ART[107].

Hartland Thomas acknowledged the distaste among some of his colleagues for the perceived strict 'functionalism' of industrialised architecture (this was a common complaint about continental modernism from British architects[108]). He proposed a compromise involving the introduction of a 'human' basis through the 'aesthetic' of classical geometric proportion. The new aesthetic, Hartland Thomas proclaimed, was to be based on ancient aesthetic ideals of 'Scale, Modulus, Proportion […] Symmetry and Balance'[109]. This was to reinvest the practice of architecture with the status of 'ART' in its appeal to ancient aesthetic tradition, thus maintaining the architect's role as author. Following his article, further discussion of mathematical proportion ensued within the British architectural press in the following years[110].

In a book for the 'intelligent layman', *Building is Your Business* (1947), Hartland Thomas elaborated on one of the pillars of his aesthetic system, 'Modulus', or the election of a single 'dimensional unit' as the basis for

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New Brutalism (London: The Architectural Press, 1966), pp. 14-15. See also Crinson and Lubbock.
[106] Neumann, pp. 197-8.
[107] Mark Hartland Thomas, 'Aesthetics the Vanguard Now', *Architectural Design*, February 1947, pp. 36-37 (p. 36).
[108] Benton, 'The Myth of Function'.
[109] Hartland Thomas, 'Aesthetics the Vanguard Now', p. 37.
[110] Neumann.

proportions throughout an individual building, which he proclaimed, brings 'spatial harmony'[111]. Emphasising its basis in classical aesthetics, he wrote that modulus

> imparts the dignity of classic regularity to a small house, for the classical order of the Greek Temples, and designs derived therefrom, were also planned on a modulus[112].

Hartland Thomas continued to pursue this ideal through his founding of the Modular Society in 1953, which promoted dimensional coordination across the building industry and architecture practice to meet the demand for cheaply produced housing. Alongside its very pragmatic aims, he also sought to preserve a foundation in classical aesthetics[113].

Hartland Thomas's preoccupation with classical aesthetics contributed to the appeal of crystallographic diagrams for him. In particular, there is a parallel to the tenets of 'modulus', as described above, in the structure of crystals, in which the repetition of a unit cell produces a larger structure. Hartland Thomas himself identified this parallel in 1947:

> The application of simple geometrical figures at the scale of man-made enclosures was a characteristically human invention. They already existed, of course, at a much smaller scale in crystalline structures, and at vastly larger scale in celestial geometry[114]

A recent and likely source of his knowledge of, and enthusiasm for, crystalline form at this time was D'Arcy Wentworth Thompson's *On Growth and Form* (introduced in chapter one). This was not only in heavy circulation among postwar crystallographers and the artists, designers and writers of the Independent Group (IG), as mentioned in chapter one, but also among British

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[111] His stated goal in writing the book was of a piece with his convictions on architecture's threatened dehumanisation; the 'intelligent layman' should weigh in on building so that it is not 'left to the technicians alone'. Mark Hartland Thomas, *Building Is Your Business* (London: Allan Wingate, 1947), pp. 7, 79-80.
[112] Hartland Thomas, *Building Is Your Business*, plate 4.
[113] Wall.
[114] Hartland Thomas, *Building Is Your Business*, p. 74

architects. It was cited by at least one other architect in postwar discussions of proportion specifically[115].

Thompson's investigation of recurring morphologies and the mathematical determinants of form in nature extended to crystals. In *On Growth and Form* he describes crystal growth:

> the snow-crystal is a regular hexagonal plate or thin prism […] Nature superadds to the primary hexagon endless combinations of similar plates or prisms, all with identical angles but varying lengths of side; and she repeats, with an exquisite symmetry, about all three axes of the hexagon, whatsoever she may have done for the adornment and elaboration of one[116].

Crystal structure, especially the way Thompson depicts it here, spoke directly to Hartland Thomas' 'modulus' ideal, and to the elements of classical geometry the architect championed. Many of the geometric ideals with which Hartland Thomas was preoccupied (geometry, symmetry and repetition of modular elements) are also found in Megaw's drawings. The forms studied and visualised by X-ray crystallographers of the postwar era did not always exhibit visually apparent geometrical order like Thompson's snow-crystals (electron density maps for example). Megaw's diagrams, however, often injected repetition where the scientist would normally omit it, and accented symmetries. As such they accord with Hartland Thomas' commitment to classical geometrical ideals even more clearly than the average unmediated crystallographers' diagram of this period might.

Hartland Thomas' enthusiasm for Megaw's diagrams specifically (as distinct from crystallographic diagrams generally) is further indicated by the fact that in 1951, when describing the aesthetic virtues, as he saw them, of the crystallographic diagram, Hartland Thomas described crystallographic diagrams *as Megaw prepared them*. He wrote in *The Souvenir Book*, 'these crystal diagrams had the discipline of exact repetitive symmetry; they were above all very pretty and were full of rich variety'[117]. Variety (as opposed to the 'dull' nylon structure) and repetitive symmetry were elements of Megaw's taste in

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[115] Neumann notes, for example, that architect Clive Entwistle references *On Growth and Form* in his article 'How to Use the Modulor', *Plan*, 9 (1951), 3-6 (pp. 3-4).
[116] Thompson, *On Growth and Form*, p. 153.
[117] Hartland Thomas, *The Souvenir Book*, p. 2.

diagrams. Hartland Thomas also wrote of the diagrams that 'like all successful decoration of the past, they derived from nature'[118]. This echoes the ethos of the South Kensington method, which involved, in Redgrave's words, the 'ornamental analysis of plants and flowers'[119]. Given the South Kensington system's continued reach in British school education in the early twentieth century, it is likely that this method of drawing affected Hartland Thomas' training as well, further predisposing him to Megaw's diagrams.

This analysis indicates that Hartland Thomas was not merely interested in X-ray crystallographers' diagrams; he was, I argue, interested in Megaw's diagrams. They were suited to appeal to Hartland Thomas because they spoke to the specific aesthetic discourse in postwar British modernist architecture circles in which he was a key figure, and to his own extremely likely South Kensington system training. The importance of the specific interests and aesthetic frameworks guiding Hartland Thomas' activities at the time, which are linked to his personal background, points to the significance of Hartland Thomas' role in the FPG as more than simply a representative of CoID interests.

CoID policy interests did, however, play a role in Hartland Thomas' enthusiasm for crystallographic diagrams and his shaping of their use in the FPG. But they did so in a way that once again reveals the effect of Hartland Thomas' own preoccupations on the project (rather than seeing him act purely as a cipher for the CoID). The CoID interest that is important here concerns the Council's aim of strengthening ties with industry. Forging stronger links and communication with industry was an important CoID objective, because it was a prerequisite to achieving the Council's goals of ensuring widespread uptake of 'good design' among manufacturers[120].

The FPG represented an opportunity for the CoID to bolster links with industry and impose 'good design' ideals at the closest level. It was unprecedented in bringing together so many manufacturers within a single

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[118] Ibid, p. 5.
[119] Redgrave and Redgrave, *A Century of Painters*, p. 564-5.
[120] As it stood at the time, the Council had a fraught relationship with the majority of British manufacturers because the modernist 'good design' principles pushed by the CoID did not accord with the tastes of most British consumers (this issue of taste is explored further in chapter three). Many manufacturers of domestic products consequently saw their economic interest at odds with the Council's cultural priorities. Woodham, 'Managing British Design Reform I'.

project under the aegis of the CoID[121]. In fact the CoID's Director, Gordon Russell, saw the FPG's value primarily in its encouragement of industrial relationships, rather than in the decorative use of crystallographic visualisations. In a 1950 letter to the CoID Chairman, R.S. Edwards, Russell described the FPG in such terms:

> Members bring their experimental work to meetings and exchange ideas. Several of them have expressed great interest in this exchange of ideas between different industries, quite apart from the decorative possibilities of the patterns themselves. It is this aspect of the matter making the project a sort of Design Centre that I think most important[122].

Russell underplayed the 'decorative possibilities' of the crystallography-inspired patterns, while lauding the project's bureaucratic possibilities. (The latter spoke more directly to CoID aims than did the notion of adapting scientific forms to pattern design.) Hartland Thomas, on the other hand, whose own aesthetic frameworks predisposed him to an interest in Megaw's diagrams, combined the two. He deployed the crystallographic diagram to pursue CoID aims to unify the industrial landscape and keep it close to the CoID's reach. Just as he sought to standardise components across the building industry through the Modular Society, launched two years after the Festival, in his administration of the FPG, Hartland Thomas sought to unify the products of different kinds of manufacturers using the crystallographic diagram as an aesthetic tool for standardisation.

Hartland Thomas aimed to use the existing formal coherences across the diagrams submitted by Megaw to unify the group's work. The crystal structure

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[121] The FPG was, historian Tom McGill has observed, a very 'direct intervention with industry and the design process' itself by the CoID (McGill, p. 98). Although this was a goal from the perspective of the CoID management, that does not mean it was achieved. Many of the participating manufacturers, as McGill points out, were CoID insiders. Their directors already sympathised with the CoID's 'good design' agenda and associated rarified modernist-influenced taste. For example, the director of the FPG textile manufacturer Barlow & Jones was Sir Thomas Barlow, the first CoID Chairman. Josiah Wedgwood, Director of the participating Wedgwood pottery firm was an original member of CoID, and Sir Ernest Goodale of another FPG textile firm, Warner & Sons, had served on the CoID board. At one point Russell urged Hartland Thomas to invite the glass manufacturer Stevens and Williams to participate in the project because he thought 'this project of yours might be used as a leader to get them to improve their design standards'. This does not seem to have come to fruition however. It was perhaps easier for Hartland Thomas to secure the participation of firms already sympathetic to the CoID's aims. Gordon Russell to Mark Hartland Thomas, 12 October 1949. DCA 5384.

[122] Gordon Russell to Dr. R.S. Edwards, 26 June 1950. DCA 5384.

diagrams had, he wrote, a 'remarkable family likeness'[123]. Hartland Thomas was adamant that this was to be maintained in the final designs. It was to provide the foundation for unity across the products by the group's disparate collection of manufacturers.

The creation of aesthetic unity across the FPG's patterns through their conformation to the conventions of Megaw's diagrams may be a factor underpinning Hartland Thomas's intent to ensure accuracy in the production of the patterns. Advice that would help maintain scientific accuracy in the FPG's designs was, as mentioned earlier, something Megaw was contracted to offer the FPG. Hartland Thomas's urge to keep the FPG's final patterns in line with an accurate representation of crystal structure is exemplified in a 1950 letter to Chance Glass, a participating manufacturer. In it, Hartland Thomas requested that a working pattern design be revised to correspond more closely to its source diagram so that it would retain its aesthetic coherence with the rest of the group's designs:

> I would say that it is essential to maintain the character of the crystal structure diagrams because of their family likeness to each other and consequently your products to the other products of the Group[124].

In this way Hartland Thomas mobilised the crystallographic diagram as an instrument for achieving co-operation. The shared formal characteristics of Megaw's diagrams served as a kind of 'modulus' for structuring coordination within the group. Here, a bureaucratic aim associated with CoID policy shaped the aesthetic use of crystallographic diagrams.

The appeal of Megaw's diagrams for Hartland Thomas thus lies in a complex set of interests conditioned by his own training, his aesthetic preoccupations (shaped by his involvement in modernist architectural circles), and the bureaucratic aims of the CoID. These factors, so far not considered in accounts of the FPG, are essential to Hartland Thomas' establishment and administering of the project.

Hartland Thomas and Megaw are, however, not the only figures whose own interests, aims, and backgrounds affected the transmission of diagrams from

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[123] Hartland Thomas, *The Souvenir Book*, p. 5.
[124] Mark Hartland Thomas to J.W. Chance, 5 April 1950. DCA 5384.

science to design for the FPG. The next section explores the reception, translation and shifting significance of Megaw's diagrams among a more extended network involved in the project's germination and shape.

Circles, networks, burning ears

This section examines the shifting significance of Megaw's diagrams as they circulated among a social network of scientists, artists and designers (and others involved in the design world). These figures were involved in the development of the FPG and its cultural transmission. My analysis of these networks furthers this chapter's argument concerning the transmission from science to design in the FPG. It shows that the cultural transmission at the root of the FPG was not one of a conveyance from one impregnable realm (science) to another (design). Rather, it was the product of already-porous discipline boundaries across which objects, texts and ideas circulated in this period. In these networks I identify further aspects of the impetus for the FPG's mission of using crystallographic diagrams as the basis for pattern designs, as Megaw's diagrams appealed to specific modernist impulses found there[125]. The following text also reveals Megaw's diagrams as a 'trading zone', a site for exchange between different disciplines[126]. Below I first describe the cross-field social networks at issue in this section and the nature of exchange among them, and then discuss their relationship to the FPG story.

Members of the Design Research Unit (DRU), to whom Megaw first sent samples of her diagrams intended as sources for designs, are important figures in these circles. They mediated relationships between scientists, designers and artists, and their interests embodied conceptual links between contemporary work in these fields. Misha Black, who was to become a shaping force on the FPG, was a founding member. Black, who was primarily an exhibition designer,

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[125] Tracing these connections necessitates touching on a number of different areas of art, design and scientists' work and practices in postwar Britain, many of which are large subjects areas that historians have studied in their own right. This section does not go into depth on the histories of each area encountered below, but rather, creates a slice across them and indicates ways in which they are interwoven.
[126] The concept of the trading zone is described further later in this section. Long, *Artisan Practitioners and the Rise of the New Sciences*, p. 8; Galison, *Image and Logic*, p. xxi.

the designer Milner Gray, and Marcus Brumwell, the head of an advertising agency, established the DRU in 1943. The director of the DRU was the art and design critic, poet, co-founder of the Institute of Contemporary Arts (ICA) and champion of modernism Herbert Read. In the postwar years the DRU members were involved in commissions for various CoID propaganda efforts including the 1946 'Britain Can Make It' exhibition, an early showcase for 'good design', and the Festival (the DRU was responsible for the exhibitions in the Dome of Discovery and Black was on the Festival's Design Panel)[127].

The DRU was embedded in networks connecting designers and custodians of postwar design reform with fine artists working in abstract modes. Read in particular acted as a social and theoretical bridge between these communities (as an art critic he was a spokesperson for British abstract art). Herbert Read's writing on industrial design, especially his *Art and Industry* (1934), counted among the influences on British 'good design' reformers[128]. Read's book spoke to reformers' drive toward the self-conscious cultivation of standards of design for industry. Inspired by the Bauhaus's aim to marry art with industry, he called for 'new aesthetic standards for new methods of production', derived from abstract artists' investigations of form[129]. The DRU shared this modernist impulse to reform British industrial design. Their founding aim 'to bring artists and designers into productive relation with scientists and technologists' reflects both *Art and Industry* and sentiments of their associates from constructivist fine art circles (introduced below) who sought communication with scientists[130].

The DRU were linked through friendships and professional ties to the 'St Ives' circle of constructivist and abstract artists, which included sculptors Barbara Hepworth, Ben Nicholson and Naum Gabo. They shared with the DRU a concern with contemporary developments in science. Science's place in the ethos and ambitions of the constructivists was articulated in the 1937 book

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[127] Atkinson.
[128] *Herbert Read Reassessed*, ed. by David Goodway (Liverpool: Liverpool University Press, 1998); Robin Kinross, 'Herbert Read's *Art and Industry*: A History', *Journal of Design History*, 1 (1) (1988), 35-50.
[129] Read, *Art and Industry*, p. 57-58.
[130] Michelle Cotton, *Design Research Unit 1942-72* (Cologne: Buchhandlung Walther König, 2011), p. 29.

Circle: International Survey of Constructive Art[131]. It expresses enthusiasm for new scientific discoveries and investigative powers, and their prospective role in art (these artists positioned themselves within a British legacy of drawing upon nature[132]). They also looked to contemporary scientific advances as a potential peaceful force and contributor to the future social progress they imagined. But they also expressed concerns about science's social role, prompted by a perceived estrangement of science from other cultural realms[133].

Some crystallographers, notably Bernal and Lonsdale, shared the constructivist artists' concerns and socialist principles, and were self-conscious about the social function of their field[134]. Bernal in particular became closely integrated into their circle as a result of this shared interest, and contributed an essay to *Circle*, calling for greater links between science and art, and for both artists and scientists to work toward a greater degree of social purpose and self-consciousness in their work[135]. His impact on the group is evident in Hepworth and Gabo's enthusiasm for crystal structure. Art historian Robert Burstow writes of the reasons for this, arguing that geometric form, including that found in crystals, symbolised 'order, precision, predictability, universality' for the constructivists, and thus the social utopian potential they saw in science[136]. Additionally, this circle was preoccupied by structures in nature more generally. They were among the British avant-garde's enthusiastic readers of Thompson's

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[131] *Circle: International Survey of Constructive Art*, ed. by Naum Gabo, Ben Nicholson and J.L. Martin (London: Faber and Faber, 1937).
[132] Martin Kemp, *Visualisations: The Nature Book of Art and Science* (Berkeley and Los Angeles: University of California, 2000).
[133] Robert Burstow, 'Geometries of Hope and Fear: The Iconography of Atomic Science and Nuclear Anxiety in the Sculpture of World War and Cold War Britain', in *British Art in the Nuclear Age*, pp. 51-80; Anne J. Barlow, 'Barbara Hepworth and Science', in *Barbara Hepworth Reconsidered*, ed. by David Thistlewood (Liverpool: Liverpool University Press, 1996), pp. 95-107.
[134] Lonsdale was a vocal pacificist. Bernal's extensive political activities included advocating state planning of science. See J.D. Bernal, *The Social Function of Science* (London: Faber and Faber, 2010 [1939]); Kathleen Lonsdale, *Is Peace Possible?* (Penguin, London, 1957). On Lonsdale's political convictions and activities, see also Baldwin and Dorothy M. C. Hodgkin, 'Kathleen Lonsdale. 28 January 1903 - 1 April 1971', *Biographical Memoirs of Fellows of the Royal Society*, 21 (1975), 447-484. On Bernal's, see also Brown; *J.D. Bernal*; Wilkie.
[135] J.D. Bernal, 'Art and the Scientist', in *Circle*, pp.119-123. Burstow; Barlow.
[136] He acknowledges however that its precise imprint is difficult to pinpoint in their sculpture, especially as the artists studied mathematical models also, the geometric forms of which are clearly evident in their work and resemble the geometric forms of crystals. Burstow, p. 60.

On Growth and Form (it possibly circulated in this milieu by way of Read, who quotes from Thompson's book in a discussion of form in *Art and Industry*[137]).

The postwar exchange between crystallographers and constructivists was not only conceptual. It was also material. For example, while at Birkbeck, Aaron Klug commissioned a London-based constructivist artist, John Ernest, to build large-scale Polystyrene virus models based on his and Franklin's virus research for the 1958 Brussels World's Fair (Figures 38 and 39). Klug remembers commissioning Ernest in part because the artist needed money at the time, knowledge which points to their shared social circles[138]. Diffraction photographs by Lonsdale also circulated among postwar artists. Several appeared alongside constructivist artworks in American constructivist artist Charles Biederman's book *Art As the Evolution of Visual Knowledge* (1948) (Figures 40 and 41)[139].

Figure 38 Artist John Ernest with Polystyrene poliovirus model constructed based on Klug and Franklin's research in 1958 at Birkbeck College.

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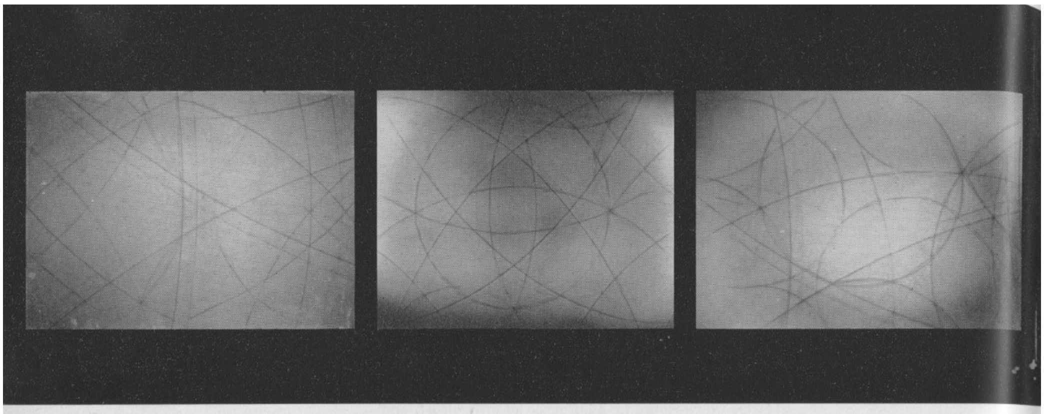
[137] Art historian Martin Kemp writes that Herbert Read introduced Gabo to *On Growth and Form* sometime while Gabo was living in Cornwall during and just after the war. Martin Kemp, 'Doing What Comes Naturally: Morphogenesis and the Limits of the Genetic Code', *Art Journal*, 55 (1) (1996), 27-32.

[138] Aaron Klug interviewed by Tony Crowther and John Finch.

[139] Charles Biederman, *Art As the Evolution of Visual Knowledge* (Red Wing, Minnesota: Charles Biederman, 1948). British constructivists enthusiastically received the book, which sought parallels between scientific and constructivist forms in reflection of Biederman's idea, correspondent with those of the St Ives circle, that abstract art should be intimately engaged with the structures of nature. Alastair Grieve, 'Charles Biederman and the English Constructionists I: Biederman and Victor Pasmore', *The Burlington Magazine*, 124 (954) (1982), 540-549.

Figure 39 Artist John Ernest building Polystyrene tobacco mosaic virus (TMV) model based on Klug and Franklin's research in 1958 at Birkbeck College.



189. Kathleen Lonsdale, Divergent beam X-ray diffraction patterns from single crystals of diamond. (Reproduced from the Philosophical Transactions of the Royal Society of London, March, 1947, by permission of the Council of the Royal Society and of the author.)*

Figure 40 Diffraction photographs of diamond crystal by Kathleen Lonsdale, reproduced in Biederman's *Art As the Evolution of Visual Knowledge*.

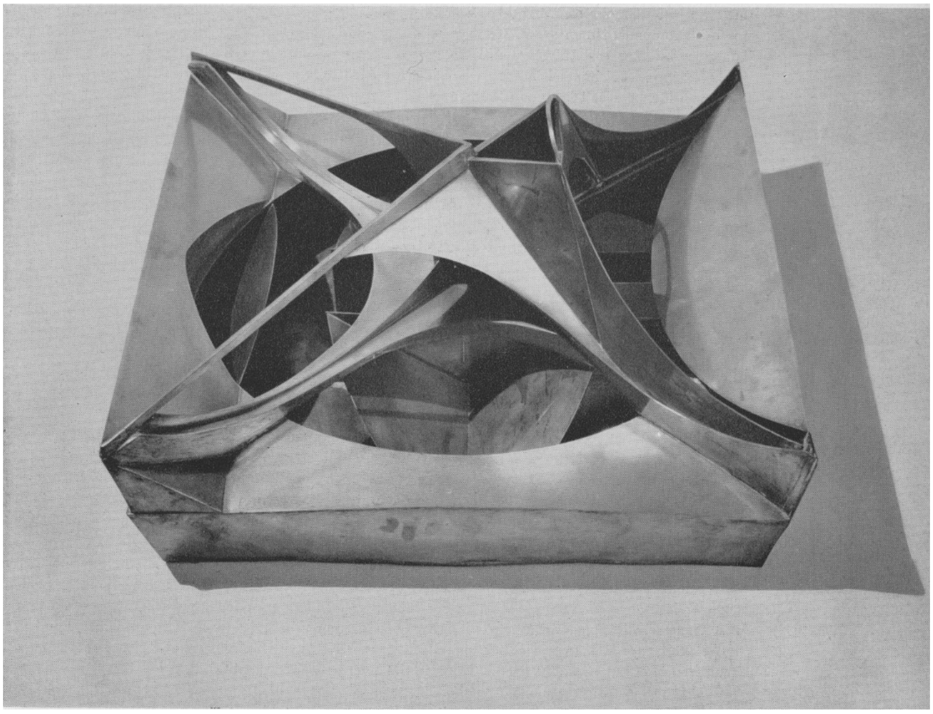


Figure 41 'Construction in Brass' (1927) by constructivist artist Antoine Pevsner (brother of Naum Gabo), featured in Bierderman's *Art As the Evolution of Visual Knowledge* on the page facing Lonsdale's diffraction photographs in the figure above.

Megaw's diagrams count among the objects that comprised the material exchange among these cross-field networks. Their circulation began when she sent several crystallographic diagrams (produced with pattern design in mind) to the DRU in connection with her proposal to them, mentioned earlier, that they be used in the production of wallpaper and textile patterns. This occurred because she was in contact with the DRU as a result of the particular social networks highlighted in this section. Bernal was the catalyst for their correspondence, as we see in a letter Megaw received from the DRU in 1945. It came from Brumwell, who wrote:

> My friend Desmond Bernal was telling me about you and I expect your ears burned at the time. I have something on which I believe you could help, at any rate he suggested you were just the person'[140].

Brumwell contacted Megaw in connection with the DRU's search for a scientist who might be interested in serving as a consultant for them. He wrote to Megaw

[140] Marcus Brumwell to Helen Megaw, 11 July 1945. AAD 1977/3/8.

again a few months later with a specific consulting job in mind for her (involving the DRU's contribution to the upcoming 'Britain Can Make It' exhibition for a section displaying designers' predictions of future products)[141]. Megaw declined, writing, 'my ideas don't run along that kind of inventiveness'. But she had a different idea she wanted to share, and wrote of her proposal concerning the use of diagrams as decorative patterns, including sample diagrams with her letter[142].

The diagrams Megaw had enclosed intrigued Brumwell. He must have seen a link with the concerns of the constructivists in the patterns she had drawn, because he lent her his beloved copy of *Circle*[143]. He also forwarded her diagrams to his friend Hepworth, who encouraged Megaw's proposal. The artist advised, 'The main point seems to me to produce them [...] exactly as they really are'[144]. Hepworth's response is consistent with the constructivists' reception of crystalline form that Burstow describes. It also indicates that Megaw's particular diagrams *as they were* spoke to the geometrical order that symbolised the abstract artists' utopian convictions (as noted earlier, not all postwar crystallographers' diagrams necessarily possessed clear geometrical features).

Hepworth was not the only figure in this network whose particular aesthetic interests were animated by Megaw's diagrams. Megaw's correspondence with Brumwell caught the attention of Read as well, who invited her to write an essay for a volume he was editing. She submitted the essay, 'Pattern in Crystallography'. Most of this essay is a fairly technical description of crystallographers' techniques. However, it also includes Megaw's reflection on the aesthetic qualities of the structures of nature. 'It is often put forward as a professed aim of science to gain control of the processes of nature', she wrote, 'but to most scientists, perhaps, an appreciation, however inarticulate, of the pattern underlying these processes is the driving force of their work. For crystallographers these patterns are readily translatable into visual terms'[145].

Megaw's pronouncement on crystallographers' revelation of the patterns of nature echoes the ideas concerning recurring patterns and morphologies in

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[141] Marcus Brumwell to Helen Megaw, 12 February 1946, AAD 3/9-1977.
[142] Helen Megaw to Marcus Brumwell, 20 February 1946. AAD 1977/3/12.
[143] He described the book as 'rather an apple of my eye' (when asking Megaw to return it some time later). Marcus Brumwell to Helen Megaw, 29 May 1947. AAD 1977/3/27.
[144] Copy of letter from Barbara Hepworth to Marcus Brumwell, enclosed in letter from Brumwell to Helen Megaw, 15 March 1946, AAD 1977/3/15.
[145] Helen Megaw, 'Pattern in Crystallography', November 1946. DCA 1466.

nature that were circulating among postwar networks of artists and designers inspired by *On Growth and Form.* Brumwell made this connection. In a letter informing Megaw that Read's book would not go ahead, Brumwell mentioned that Read was involved in a new project, which he said was based on 'the D'Arcy Thompson idea which is the same as yours'[146]. This new project was the ICA exhibition 'Growth and Form', spearheaded by artist and designer Richard Hamilton of the IG. This is a significant statement to make, given the resonance of Thompson's ideas among designers and artists in these networks, and suggests some roots of their interest in Megaw's materials (indeed, as noted earlier, the book's ideas may have also predisposed Hartland Thomas to Megaw's diagrams).

The DRU did not ultimately pursue Megaw's proposal. But the impetus for their interest in crystallographic diagrams (identified here as corresponding to modernist aesthetic frameworks associated with abstract art) is important to the shape of the FPG. This is because Misha Black of the DRU played a significant role in the project, weighing in on individual designs and the character of the project as a whole throughout the FPG's working period. In *The Souvenir Book*, Hartland Thomas writes that Black's involvement with the FPG was a 'happy chance', because Black, a member of the DRU, was 'already sympathetic to the idea'[147].

Black was another guiding force in the FPG whose role has escaped interpretation. This may be because his reflections are not well represented in the archive; Black and his fellow DRU collaborator Alexander Gibson frequently met with designers and manufacturers outside official FPG meetings (often in situ at the Regatta Restaurant). But the minutes of the first meeting of the FPG in 1949 indicate the appeal of the diagrams for Black. He enthused that 'the crystal patterns provided the designer with a new basis for evolving 'abstract' shapes arising not from aimless inventions but from natural forms'[148]. In addition to speaking to a modernist aversion to 'superfluous' decoration, Black's comment shows that he clearly shared an appreciation of the 'abstract' crystallographic diagram with the constructivist artists and with Read, with whom he associated,

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[146] Marcus Brumwell to Helen Megaw, 28 November 1949. AAD 1977/3/35.
[147] Hartland Thomas, *The Souvenir Book*, 5.
[148] 'Draft Report of the First Meeting of the Festival Pattern Group', 16 December 1949. DCA 5396.

and whose ideas inflected the founding principles of the DRU. (Black claimed he even wanted to be a fine artist himself but chose ‘commercial art’ to ‘avoid malnutrition’[149].)

Lonsdale, who was in frequent communication with designers and artists of these circles, is the final important figure in this network to consider in terms of the FPG’s germination[150]. Through her 1949 SIA talk, entitled ‘Patterns Observed by the Scientist’, in which Hartland Thomas saw Megaw’s diagrams, Lonsdale was involved in the initial transmission of diagrams to the design context that inspired the FPG[151]. And like Megaw, she did not transmit them unmediated. Rather than simply present scientific knowledge in her lecture, she cast molecular structures as modernist designed objects. This is evident from notes in her archive for a talk given earlier on the same material.

Lonsdale had given a lecture at UCL a few months before the SIA event, and notes in her archive for both lectures indicate she recycled much of the material (she also used Megaw’s diagrams in both). Her SIA lecture notes list key phrases that match points from the more thoroughly written-out lecture notes for the earlier UCL event. One point in her SIA talk notes reads ‘RR - W.L.B. transformed chemical riddle into a system of simple and elegant architecture’[152]. This line refers to a 1947 comment by the then-president of the Royal Society, Robert Robinson recognising W.L. Bragg’s research on silicates[153]. The corresponding text in Lonsdale’s more detailed UCL lecture notes reads:

> Work on silicates described by Pres. Roy. Soc. as having “transformed a chemical riddle into a system of simple and elegant architecture” – no embellishment in the form of gargoyles or spires, - work on structure of biological substances showing similar evidence of fundamental simplicity

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[149] Avril Blake, *Misha Black* (The Design Council, London, 1984), p.14.
[150] For example, Lonsdale played a role in the ‘Growth and Form’ exhibition. Space does not allow for more detailed discussion of her involvement in these circles, which is as yet under-explored and is a subject for future research.
[151] Advertisement for Ashridge summer school, *Journal of the Society of Industrial Artists*, April 1949, p. 9-10.
[152] Kathleen Lonsdale, ‘Lecture to Society for Industrial Artists, Ashridge, Berkhamsted, 14.5.1949’. Kathleen Lonsdale Papers, National Archives, E.504.
[153] The original quote is from Robert Robinson, ‘Address of the President Sir Robert Robinson, At the Anniversary Meeting, 30 November 1946’, *Proceedings of the Royal Society A*, 188 (30 January 1947), 143-160 (p. 43).

> of design, functional simplicity exhibited in an almost infinite variety of natural forms[154].

Lonsdale's SIA audience that day would have recognised her framing of molecular structures in explicit terms of the modern movement's eschewal of ornamental 'embellishment' and commitment to 'functional simplicity of design'. It is impossible to know the precise effect of Lonsdale's modernist framing of molecular structure on Hartland Thomas's response that day. What is clear, however, is the mediation of crystallographic diagrams by scientists in the networks I am tracing. Even before it reached actors in the design profession, scientists framed crystallographic subject matter in accordance with design in specific ways: Megaw as detailed earlier, and Lonsdale in her formatting of molecular structure distinctly in the language of architectural modernism. Lonsdale was capable of this because she was not isolated from reigning aesthetic concerns in modernist art and design circles, as a participant in the networks traced in this section.

In the story of the FPG's cultural transmission, the crystallographic diagram is not merely a passive object dispatched from science to design. The above discussions demonstrate that the crystallographic diagram was, itself, a site for translation and transmission, not only from science to design, but also – as Megaw and Lonsdale's mediation of the diagram indicate – a site in which ideas and conventions of design inflected scientific visualisation. The crystallographic diagram is a 'trading zone' between conventions, tastes, and ideologies associated with design and art, and the conventions and knowledge associated with crystallographic visualisation. Historian Pamela O. Long evokes the concept of the 'trading zone' in her research on the effect of knowledge exchange between artisans and 'learned men' in the development of the 'scientific revolution' in early modern Europe[155]. 'Trading zones' are sites

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[154] Kathleen Lonsdale, 'Lecture on 'Art and Architecture in Science', 18 January 1949', Kathleen Lonsdale Papers, National Archives, E.503.

[155] The concept derives from anthropology, and is closely related to Mary Louise Pratt's notion of 'contact zones' between cultures mentioned in the thesis introduction. As also noted in the thesis introduction, Long draws upon Galison's use of the 'trading zone' concept, which described communication between practitioners in physics purveying different kinds of knowledge and 'technical traditions'. Galison adapted the concept from anthropology research on cultural

allowing for the exchange of knowledge between different cultures. They might be physical sites (coffee shops, for instance) or symbolic ones (in Long's text, she describes the Vitruvian tradition in architecture as a 'trading zone'). The crystallographic diagram is a symbolic 'trading zone'. Examination of the FPG reveals the diagram as a site that sees the importing of conventions and tastes associated with design into the work of the scientist (as revealed by Megaw's production of 'decorative' diagrams and Bragg's conceptualisations of crystal structure through decorative art). And as the analysis of social networks above indicates, the crystallographic diagram was also a site for communication and exchange of ideas among practitioners in different fields.

The cultural transmission of crystallographic diagrams to the industrial design context for the FPG was thus part of an on-going conversation across disciplines, which had roots in a number of modernist practices. This differs from existing narratives of the FPG, in which a note of inevitability attends reflections on the FPG's use of crystallographic diagrams. Forgan offers, 'designs drawn from science in this way were self-evidently essentially modern and abstract' and 'interest in science was widespread and characteristic of the time'[156]. Schoeser links the FPG with an ''exploratory' zeitgeist' of the period[157]. Authors often simply quote (without interpretation) Hartland Thomas' own justification for the use of the diagrams in *The Souvenir Book* that 'they were essentially modern because the technique that constructed them was quite recent, and yet, like all successful decoration of the past, they derived from nature'[158].

The sense of inevitability in much historiography also derives from the fact that, on the surface, the FPG's cultural transmission between science and design seems to be easily 'explained' by the Festival context in which it appeared. As a project marrying industrial design with a scientific field in which British scientists were prominent, the FPG clearly matches two Festival aims: to celebrate British achievement in science and in industry. It corresponded to the Festival's optimism for a future led by science, and echoed the theme of the

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hybridisation. Long, *Artisan Practitioners and the Rise of the New Sciences*; Galison, *Image and Logic*, p. xxi.

[156] Forgan, 'Festivals of Science', p. 225, 223.

[157] Schoeser, 'The Appliance of Science', p. 124.

[158] Hartland Thomas, *The Souvenir Book*, p. 5.

structure of matter on display at the Exhibition of Science in South Kensington. The FPG also corresponded with representations of science at the Festival as safe, since X-ray crystallography dealt with structures made up of atoms rather than the atomic physics that birthed the bomb. Forgan has shown that 'all mention of the arts of war was excluded' from the exhibitions[159]. Additionally, the Festival also provided a potential platform for presenting FPG designs to consumers as part of its general 'good design' propaganda. Historians have therefore described the FPG in terms of the Festival's goals for science and design[160].

This correspondence no doubt helped secure the FPG project as part of the Festival after Hartland Thomas conceived the scheme, but the FPG's cultural transmission between science and design was more than merely a way to combine Festival goals and present an optimistic face of the 'atomic'. I have shown here that the roots of the FPG's mission to use crystallographic diagrams is a much more complex story. The above discussion of the circulation of Megaw's diagrams showed that these visualisations appealed to several specific, and slightly varying, contemporary interests in which aspects of current science served particular ideological or aesthetic aims (including hopes for a social utopian future and classical ideals of proportion emanating from architectural debates). The FPG cannot be explained through notions of a generalised period interest in science or a desire to draw upon science for the sake of interdisciplinary connection itself. Hartland Thomas, Read, Hepworth, Brumwell and even Lonsdale (who classed molecular structure in the context of anti-ornament ideals of the modern movement in architecture) all positioned crystallographic visualisations within the context of different ideas circulating in these networks at the time.

Conclusion

This chapter shows the transmission of scientific diagrams to the design community in the case of the FPG to be more complex than has been previously

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[159] Forgan, 'Festivals of Science', p. 233. See also Forgan, 'Atoms in Wonderland'.

[160] Jackson, *From Atoms to Patterns*; Conekin, *'The Autobiography of a Nation'*; Forgan, 'Festivals of Science'; Jonathan Woodham, *Twentieth-Century Ornament* (London: Studio Vista, 1990).

acknowledged. This cultural transmission emerges from a network comprising actors operating within different (sometimes connected) frames, the diagrams themselves, policies, practices and tastes. Agency in this transmission is delocalised; the network traced here displays an emergent property central to Bennett's thinking on networks. 'The locus of agency is always a human-nonhuman working group', she writes[161].

The analysis of the FPG advanced in this chapter reflects the interdisciplinary perspective of this research. In fact as this chapter demonstrates, understanding how the crystallographic diagrams in question changed – in form and significance – across social networks spanning science, design and art fields (now in the hands of a crystallographer, now before mandarins of industrial design policy), requires an interdisciplinary perspective. Its ramifications likewise do not sit within only one discipline. The resultant investigation yields a clear picture of just how these visualisations operated in various contexts, which speaks to broader concerns developed within both history of design and history of science scholarship.

This chapter reflects on overarching questions about the history of postwar British design pursued in this thesis: it furthers understanding of the aesthetic frameworks operating in postwar British circles aligned with modernist design that conditioned cultural transmission between crystallography and design. Empirical examination of the responses of various actors to Megaw's diagrams sets the various aesthetic frameworks, ideologies and – in Hartland Thomas' case – bureaucratic concerns at the root of the FPG's aesthetic mission into sharp relief.

The narrative of the FPG presented here comes some way toward de-essentialising categories of 'science' and 'design' as scholars from both fields deploy them in discussions of cultural transmission between the two. This emanates in part from my methodological starting point: the analyses in this chapter approach 'science' not as the monolithic impermeable category that it often is in design histories. The chapter also results in a complication of historical categories related to industrial design. It took analysis of the FPG outside the CoID focus that characterises much recent research on postwar

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161 Bennett, p. xvii.

British design[162]. Such research provides a valuable foundation for this study, but this chapter reveals that in the case of the FPG, a scheme that looks on the surface like one of the CoID's design promotion efforts is actually best understood through a range of contexts in which the CoID's overarching goals count as merely one of many contexts (including the design training of a scientist and aesthetic ideologies in architecture and constructivist art). And in the history of postwar British modernist design reform, which was a distinctly masculine project, this narrative of the FPG reveals an instrumental role played by a woman, Megaw[163]. Her proposal was not simply brought to fruition by the figures and structures associated with postwar design policy. Instead, Megaw literally shaped the character of the project through her mediation of the FPG's diagrams.

A further factor complicating the notion of the CoID as a historical category is this: even though the FPG, as I have described it, reveals a network of actors that represent interests outside that of the key characteristics of CoID policy, many are nevertheless intertwined with the CoID through ideological strands or in practical ways. Hartland Thomas is the most obvious example (he was guided by CoID imperatives in a general sense, but in gravitating toward Megaw's diagrams, responded to different interests). Consequently, this analysis demonstrates the difficulty of thinking about the CoID or even postwar British modernist design reformers as a monolithic category. The FPG's use of crystallographic diagrams as the basis for pattern design betrays the mark of several modernisms active in postwar British design, art and – as we see with Lonsdale and Bernal – science networks. One does not need to look far from the policy-making centre of the CoID elite to find a network teeming with ideological variety[164].

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[162] Hayward, ''Good Design Is Largely a Matter of Common Sense''; *Design and Cultural Politics in Postwar Britain*; Woodham, 'Managing British Design Reform I'; Woodham, 'Managing British Design Reform II'.

[163] On the sexual politics of modernist design reform see Sparke, *As Long As It's Pink*. She describes early twentieth-century design reform as 'a thinly-disguised attempt by masculine culture to set the cultural terms of reference for modernity such that women, with their new-found power as consumers, would not take over the reins' (p. 12). I lack space to discuss it here, but the relationship of Megaw's involvement in the FPG to the sexual politics of postwar British modernist design reform and practice (and simultaneously that of the culture of postwar British X-ray crystallography) presents subject matter for future research.

[164] This complements recent research by Glenn Hooper into the design critic, historian and novelist John Gloag. Hooper points out that histories of British modernist design class him as part

A further result of this analysis, which at first appears as a contribution to design history but also suggests avenues for the history of science, is that it offers a glimpse into the effects of the South Kensington system. Despite the many published accounts of it, little is known about the subsequent resonance of this type of training[165]. My research reflects on its resonance, or the 'consumption' of the South Kensington system, locating it in territory where design historians might not typically look for it – in the work of a scientist, and in the FPG, which is so indelibly attached to postwar period style in design historiography. This suggests possibilities for future research into the effect of the South Kensington schools not only upon designers, but also on those in other professions. It also suggests the potential of future research on the role of early education in design drawing on the visualisation practices of scientists.

The FPG represents an opportunity to study the place of X-ray crystallography in postwar British culture - not in terms of its consumption in the public widely (because FPG prototypes did not have an extensive commodity life in this way[166]). Instead, the result of this study is a complex and contingent picture of how scientific representations functioned outside the laboratory in cultures of practice associated with design policy, production, and fine art including the members of the DRU and Hartland Thomas (as the modernist architect *and* as the CoID officer). These actors, who represent different publics for science, negotiated crystallographic knowledge in different ways, correspondent with their own specific interests, aesthetic or practical goals, or the purpose science served in their worldview (illustrated well by the constructivist interest in the crystallographic diagram).

In these various environments, crystallography did not operate in any single way, but in multiple ways, appealing to specific interests operating in different circles. For example, for Hartland Thomas it spoke to his convictions

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of the cadre of design reformers associated with the CoID, or a 'vanguard of the cultural elite', yet Gloag himself has been under-studied. Hooper shows that Gloag's ideals and hopes for British design differ in many senses from the way design historians describe the convictions of this 'vanguard' of British modernist design reformers. This too points to the multiplicity of positions bubbling just below the surface of the reformers' policy-making. Hooper, p. 1.

165 Arindam Dutta's research ventures into the area of the effects of the South Kensington system also in very different territory: India. Dutta examines the resonance of this system implemented as part of British colonial rule in India and in the context of the dissemination of taste. Dutta.

166 Most of the FPG prototypes were never commercially produced (Jackson, *From Atoms to Patterns*). Consumption is a larger theme in part two of this thesis, which focuses on designed objects that had a more extensive commodity life: ball-and-rod furnishings.

about the classical/modernist inspired aesthetic ideals that could ward against the effects of industrialisation on the designer; for Black (the DRU member and would-be fine artist) the crystallographic diagram revealed a kind of abstraction discussed in his circles for years; for Lonsdale – on a day outside the laboratory – crystallographic diagrams presented an opportunity to communicate with modernist designers on their own terms. And as becomes clear in the next chapter, it is just as significant that for others, such as Gordon Russell, crystallographic diagrams inspired very little enthusiasm.

The FPG is not representative of a wider deliberate use of crystallographic visualisation in postwar British industrial design. But in the ways described above, it becomes clear that the FPG, for all of its exceptionality, is nevertheless representative of this thesis' findings on X-ray crystallographic visualisation in postwar British material culture. It speaks to the shifting and multiple uses and meanings of crystallographic visualisation - whether that is within scientific practice, at the intersection of practices and in its consumption outside the lab (as seen here), or in the wider public consumption of artefacts (discussed in the second half of the thesis). As this narrative of the FPG indicates, X-ray crystallography was, in fact, more than just a friendly version of the 'atomic'.