A SURVEY OF THE NETWORKS BRINGING A KNOWLEDGE OF OPTICAL GLASS-WORKING TO THE LONDON TRADE, 1500-1800

Anita McConnell

Edited by

Jenny Bulstrode

Figure 1: 'Venetia', by the Italian designer, engraver and dealer in books and prints Giacomo Franco, 1597. The hand-coloured engraving shows Venice with the island of Murano top centre right. Murano hosted the origin of European glass-working in an attempt to sequester and monopolise the valuable skills of the Levant glass-makers implanted there. The engraving highlights the containment of the islands state. Nonetheless, it was from here that skilled knowledge of glass-working moved with people through Europe and to the London trade. Giacomo Franco, Venetia, 1597, Peacay, bibliodyssey.blogspot.co.uk, CC BY 2.0.

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Foreword

In October 2013, Simon Schaffer and I received the following email from our friend and colleague Anita McConnell:

> many years ago Gerry Martin gave me some money to investigate how the technology of glass working for optical purposes reached Britain, 1600-1800. This was done [in 1997] and Gerry read it, apparently with pleasure, but nothing more was done prior to his death. Subsequently, a paper copy was lodged in the Institute of Historical Research where it was seen by those who knew of its existence (such as Inge Keil), and I made some revisions... Years then passed… and I still hope that the monograph could see the e-light of day somewhere.

Simon responded: 'This is of course a first rate account of glass technique, with no equivalent research-based text in English, and if there were any way of making it more accessible, that would be very welcome indeed. I would also hope that there might be a facility for linking this text with its related images.'

It was therefore decided to organise a way to bring Anita's 'Glass Monograph' (as we fondly refer to the project) to e-daylight, by publishing it as a pdf freely available on the website of the Whipple Museum of the History of Science (www.cam.ac.uk/whipple).

The Whipple Museum is immensely proud to sponsor the publication of this outstanding work of scholarship on the history of optical glass-making and -working, and to be able to share it freely with all who are interested in the subject. Furthermore, we are delighted by the opportunity to provide illustrations for this volume of various objects in our collection as well as from the numerous publications referred to in Anita's text and held in the Whipple Library's rare book collection.

In order to bring the project to daylight it was necessary to do some additional work, not least to source the 'related images' and provide their captions. Jenny Bulstrode, currently a doctoral candidate in the Department of History and Philosophy of Science, and Joshua Nall, Curator of Modern Sciences at the Whipple Museum, generously agreed to do the necessary work, with Jenny kindly taking on the role of editor. Steve Kruse, another Whipple Museum staff member, and Anna Jones, Whipple Librarian, also contributed expertise and time to the project. Toby Bryant, another doctoral student in HPS, compiled the Index. The resulting publication of Anita's 'Glass Monograph' has been a collaborative project; first begun in 1997, we are very pleased to now be able to share it widely in this modern format.

This project also represents a labour of love: love of the study of scientific instruments, and love for Anita herself. Anita was a great friend to the Whipple Museum, giving support over many years for student interns to work on the collection, donating numerous books from her own collection, and above all contributing her time and vast knowledge whenever it was needed. Through her, we learned a great deal. Prior to her death, we showed her the 'almost ready' version of this work. Now that she is gone, we are honoured to share this 'Glass Monograph' as a memorial to her scholarship and her friendship.

Liba Taub
Director and Curator
Whipple Museum of the History of Science
October 2016

Preface and acknowledgements

This investigation of the networks that brought knowledge of optical glass working into the London workshops between 1500 and 1800 was undertaken at the request of Gerry Martin (1930–2004), of the Renaissance Trust. Early in his life Gerry became fascinated in the way things were made and took up an apprenticeship with an engineering firm. After some months in Chicago he returned to England and began a long association with a company making temperature control systems. Under Gerry's management the firm prospered, and set up branch companies around the world. This financial success provided the money to found the Renaissance Trust in 1968. Through the Trust Gerry pursued his interests in the transmission of technical knowledge. Between 1990 and 1995 he set up The Achievement Project, holding annual symposia to look at aspects of achievement and creativity, recruiting contributors from Europe and the United States who were working in allied fields. From this developed 'The Growth of a Skilled Workforce' project. Fascinated by scientific instruments, Gerry built up his own collection and supported museums of science. In addition, he provided funding for several students and academics, including my own history of the scientific instrument firm Cooke, Troughton & Simms (1992).

Gerry was intrigued by how the knowledge of glass working of lenses for optical instruments, namely spectacles, telescopes and microscopes, in the period 1500 to 1800 had been transmitted across Western Europe to London, and in 1995 asked me to investigate. My researches yielded material of such diverse nature and quality that the first problem was to find a way of structuring it. To Gerry I owe the present format of a series of thematic chapters.

There are three elements to any lens, whatever its size and type: the material, usually but not inevitably glass; an understanding of the curvature needed to fulfill the purpose of the lens; and the tools to shape and polish the material accordingly. These three skills, broadly chemical, mathematical and technical, originated in different places and travelled in different ways. The knowledge of fine glass making was carried by the migrations of the glass-makers themselves. Its implantation abroad was delayed by their reluctance to pass on trade secrets. Beyond a basic rule of thumb, mathematics was needed to calculate refraction and determine how best to shape and combine lenses for the desired effect. For this reason, mathematically-minded virtuosi had to collaborate with the lens grinders. The machinery which speeded up lens grinding, and which was devised in pursuit of the non-spherical lens, could not easily be transported from place to place.

However, it could and was described and illustrated, and books dealing with this subject multiplied in the later seventeenth century.

Significantly for the movement of glass-making knowledge, the mobilization of these elements required a customer with sufficient money. The major advances in lens grinding took place during those periods of strong demand underpinned with the necessary funds. By purchase or gift, lenses and small instruments found their way across Europe. Would-be users also travelled, observing and comparing the products of this or that maker. Lens grinding, like ornamental turning, was considered a polite art, one that could be practised by gentlemen. Numerous amateur and professional astronomers prepared their own lenses. In consequence, optics, astronomy and microscopy were subjects of consuming interest to a considerable body of people. This generated a vast correspondence, much of which has survived, and is now available to students.

I have drawn on a wide range of sources in England, Germany, Italy, the Netherlands, France and Switzerland, and am obliged to librarians and archivists who patiently bore with my requests. The first drafts of this work went to Silvio Bedini, Gloria Clifton, Derek Keene, Inge Keil, Ian Freestone, Allen Simpson, Anthony Turner and Michael Wright, all experts in their fields, and I am grateful for their advice and comments. Others who smoothed my path include Cathy Ross, Jan Deiman, Giorgio Dragoni, Wendy Evans and Alison Morrison-Low. Without the generous sponsorship of the Renaissance Trust the project would never have been contemplated, and for the most generous sharing of information and assistance with German texts I should particularly thank the late Inge Keil of Augsburg.

Anita McConnell
April 1997
(revised 2010, 2011, 2014)

Figures

Tables

Abbreviations

Arch. Nat. Archives Nationales, Paris, France.

Beeckman. Cornelis de Waard (ed.), *Journal Tenu Par Isaac Beeckman de 1604 à 1634*, The Hague, (4 Vols., 1939–53).

Bibl. Inguim. Bibliothèque Inguimbertine, Carpentras, France.

Birmingham. Birmingham Public Library, Birmingham, United Kingdom: Boulton and Watt Correspondence.

BL. British Library, London, United Kingdom.

BL Lans. British Library, London, United Kingdom: Lansdowne Manuscripts.

BM Prints. British Museum, London, United Kingdom: Department of Prints And Drawings.

BN. Bibliothèque Nationale, Paris, France.

Bodleian. Bodleian Library, Oxford, United Kingdom.

Bologna. Assunteria di Istituto, Archivio di Stato, Bologna, Italy.

Brera. Archivio dell'Osservatorio Astronomico di Brera, Milan, Italy.

Cal. SPD. National Archives, Kew, United Kingdom: Calendars, State Papers Domestic, 1509–1714.

Cal. SPV. Calendars, State Papers Venice, 1202–1675 (38 Vols. in print and online).

CLRO. Corporation of London Record Office, London Metropolitan Archives, London, United Kingdom.

Downshire. National Archives, Kew, United Kingdom: Downshire manuscripts.

Galileo. Antonio Favaro et al (eds.), *Le Opere di Galileo Galilei*, Florence: Barbèra (20 Vols., 1929–39).

Geneva BPU. Bibliothèque Publique et Universitaire, Geneva, Switzerland:

Manuscripts.

HP Eph. Sheffield University Library, Sheffield, United Kingdom: Hartlib Papers, Ephemerides.

HP Letters. Sheffield University Library, Sheffield, United Kingdom: Hartlib Papers, Letters.

Inner Temple. Inner Temple Records, London, United Kingdom.

Leiden. University Manuscripts, Leiden, The Netherlands.

London. Guildhall Library, London, United Kingdom: Manuscripts.

Lyon. Académie de Lyon, Lyon, France: Manuscripts.

Mersenne. Cornelis de Waard, René Pintard, Bernard Rochot, and Armand Beaulieu (eds.), *Correspondance du P. Marin Mersenne, religieux minime*, Paris: Éditions du C. N. R. S., (17 Vols., 1932–88).

NA. National Archives, Kew, United Kingdom.

Oldenburg. A. Rupert Hall And Marie Boas Hall (eds.), *The correspondence of Henry Oldenburg*, Madison; London: University of Wisconsin Press; Mansell; Taylor & Francis, (13 vols., 1965–86).

Paris Observatoire. Observatoire De Paris, Paris, France: Manuscripts.

RAS. Royal Astronomical Society, London, United Kingdom: Archives.

RGO. Cambridge University Library, Cambridge, United Kingdom: Royal Greenwich Observatory Archives.

Rigaud. S. P. Rigaud (ed.), *Correspondence of scientific men of the seventeenth century*, Oxford: Oxford University Press, (2 vols., 1841).

RS. Royal Society, London, United Kingdom: Manuscripts.

Torricelli. Gino Loria and Giuseppe Vassura (eds.), *Opere di Evangelista Torricelli*, Faenza: G. Montanari, (4 vols. in 5 pts.: I–III, 1919; IV, 1944).

Trinity Coll. Trinity College Library, Cambridge, United Kingdom.

Wedgewood. Wedgwood Museum Archives, Josiah. Wedgwood & Sons, Ltd., Barlaston, Stroke-On-Trent, United Kingdom.

Westminster Abbey. Westminster Abbey, London, United Kingdom: Archives.

Westminster Archives. City of Westminster, London, United Kingdom: Archives.

Wolfenbüttel. Herzog August Bibliothek Wolfenbüttel, Germany.

WYRO. West Yorkshire Record Office, Bradford, United Kingdom.

A vocabulary of glass and glass-working materials

The names given to various mixes of glass over the centuries are not rigid in their meanings, and account must be taken of the original language, context and date.

Types of glass

Bohemian crystal: Glass made from crushed pebbles, potash obtained by treating Beech wood ash with acid, and manganese as a decolouring agent. The melted mass was firmer than Venetian glass and could not be modelled in such fine detail but it was clear and took a fine polish. Developed by 1680, it came into prominence in the eighteenth century with the decline in Venetian crystal.

Crown glass: Glass made with sand as the source of silica, and often slightly tinted because of iron contaminating the sand. It was of medium quality, compared to crystal. Plates of the glass were obtained by blowing into flat discs or crowns, for glazing. Newton's prism, said to have been of crown glass, had a density of 2.58.

Flint glass: In the sixteenth and seventeenth centuries, crystal glass made from crushed calcined flints, obtained from the Po Valley, or other sources. Later often applied to lead crystal. Refractive indexes of flint glasses in astronomer William Gascoigne's telescope of 1641 were calculated from his observations to be, for the light flint in the object glass, 1.576, and for the very light flint eyepiece, 1.542.

Glass: Depending on its silica component, glass may be described as 'light' or 'heavy'. By the later seventeenth century 'density' was increasingly used to describe this distinction. This meant a value obtained from its mass divided by its volume, where the density of water is 1. The density of a glass controls the angle at which an incident ray of light is refracted on entering from air. Dutch astronomer and mathematician Willebrord Snel van Royen and the French mathematician René Descartes enunciated this angle at much the same time. It is now known as Snell's or Descartes' Law.

Lead glass: Lead was used as a colourant from the Middle Ages but heavy lead crystal glass was developed by George Ravenscroft in the 1690s. Dollond calculated that English lead crystal in 1757 had a density of not less than 3.22. Apsley Pellatt, writing in the 1840s, said that common flint glass had a density of 3.2, while that made for telescope lenses had 10 per cent extra lead, giving it a density of 3.25 to 3.5. In the course of the eighteenth century this glass was known in England and France as flint glass to distinguish it from crown glass, the term *façon de Venise* having by then lapsed.

Muscovy glass, slude: The mineral mica, used as an unbreakable substitute for glass, in ships' lanterns, carriage lights, etc.

Rock crystal: A mineral consisting of pure quartz, occasionally used for lenses but criticised for its high reflectivity. Could be crushed and used as the silica fraction for *cristallo*.

Strass: A dense lead glass substitute for gems, made before 1740 by Georges Fédéric Stras, then working as a jeweller in Paris. Nineteenth- century French chemist Eugène-Melchior Péligot in his 1877 text *Le verre son histoire, sa fabrication* identified its constituents as silica 38.2, lead oxide 53.0, potash 7.8, aluminium 1.0, with a trace of borax and arsenic oxide. Though brilliant, it was very soft and could be scratched not only by hard stone but by other types of glass. Its density was 4.0. The prominent eighteenth-century French mathematician and astronomer Alexis-Claude Clairaut reported having employed it in an achromatic lens in a letter of 4 August 1762.

Venetian crystal, *cristallo*: Glass made from crushed white flint pebbles from the River Po and soda from Syria. Cristallo was as clear as rock crystal. Made at Murano by the Barovier family around 1450. *Cristallino*, which earlier denoted 'like natural crystal', soon came to mean 'made of artificial crystal'. The term *façon de Venise*, which in England seems to have been restricted to crystal made from crushed flints, is ambiguous when referring to glass made in the francophone Netherlands where two types of crystal were made in Venetian furnaces, an inferior one using sand and a superior one using flint (*cristal de silex*).

Constituents

Glass-makers' soap: Pyrolusite, contains manganese which oxydises iron impurities in the glass and is itself reduced, leaving colourless glass.

Potash: Potash-rich ashes of fern were known in Venice as *alumen de fuligine*.

Soda (NaOH): Derived from ashes of the soda plant or saltwort, one of the chenopodiacae, *salsola soda* or *salsola kali*. Muranese glassmakers preferred soda from Syria, which went under the name of *alumen catinum* (alum for crucibles). Saltwort is native to sandy sea-shores in Britain but the ashes brought from Spain under the name of *barilla* were preferred. Barilla may also mean ashes of kelp.

Zaffer: An impure oxide of cobalt, used in low concentration to remove the yellow tint from glass.

Grinding and polishing materials

Bloodstone, bolus, colcothar, crocus martis, rouge: Ferric oxide, haematite, used as a polishing agent.

Corundum: Natural aluminium oxide, a crystalline substance nearly as hard as diamond. Used as a grinding agent.

Emery, emril, smiris: a coarse variety of corundum.

Putty powder, potey: Amorphous stannic oxide, calcined tin, obtained from the cinders of tin-smelters' furnaces, or calcined tin and lead, used as a polishing agent.

Rottenstone, tripoli: Diatomaceous earth, siliceous matter, used as a grinding and polishing agent. (Tripoli was named after Tripoli in Syria from where it was obtained.)

Editor's introduction
by Jenny Bulstrode

In Europe from the late middle ages right through to the nineteenth century, the skilled process of making optical quality glass was a valuable and jealously guarded asset, not only by practitioners, but also by the state in which they operated (Figure 1). Optical quality describes glass of a particularly high homogeneity that could be incorporated into an instrument to manipulate light phenomena. To realise this quality the piece of glass, called a blank, required grinding into shape and fine polishing. This process, however, was typically frustrated by the presence of bubbles and striations in the product. Coal dust in the molten batch, insufficient mixing, or an inconsistent melt all also scarred the clarity of the product and made glass unfit for optical purposes. Because of the value of optical glass, the knowledge and skill required to overcome these challenges were very closely controlled and protected. Monopolies and the excise duty were used to enforce state interests, such that the production of glass withered and flourished with restrictions and privileges. By contrast the artisanal craft of shaping lenses grew in particular in response to the demands of spectacle-makers, while the limitations of technology were pushed by an interest in lenses from dilettante virtuosi, natural philosophers and professional astronomers who made ever more demanding specifications (Figure 2).

The following chapters bring together in one place a diverse array of primary and secondary material on the networks that carried a knowledge of glass-working to the London trade. Chapter One sets out how the transmission of glass-working knowledge depended on the movement of people, while monopolies were sought and enforced by restricting this mobility. The movement of people and implantation of skills is contrasted with the dissemination of 'how-to' texts. One such text provides an account of the basic method of making glass from raw materials through much of the early modern period. Chapter Two traces the introduction of skilled Venetian and German glass-working knowledge to the London trade in the second half of the sixteenth century. Glass-working privileges were potentially lucrative and hotly contested. Through patent legislation and his extremely able wife, née Elizabeth Roper, former seaman and speculator Robert Mansell was able to dominate the market between 1615 and 1640 against fierce competition. However, it was not until the third quarter of the seventeenth century, and the development of a qualitatively different type of glass by George Ravenscroft, that the British glass industry began to dominate European production of optical quality glass.

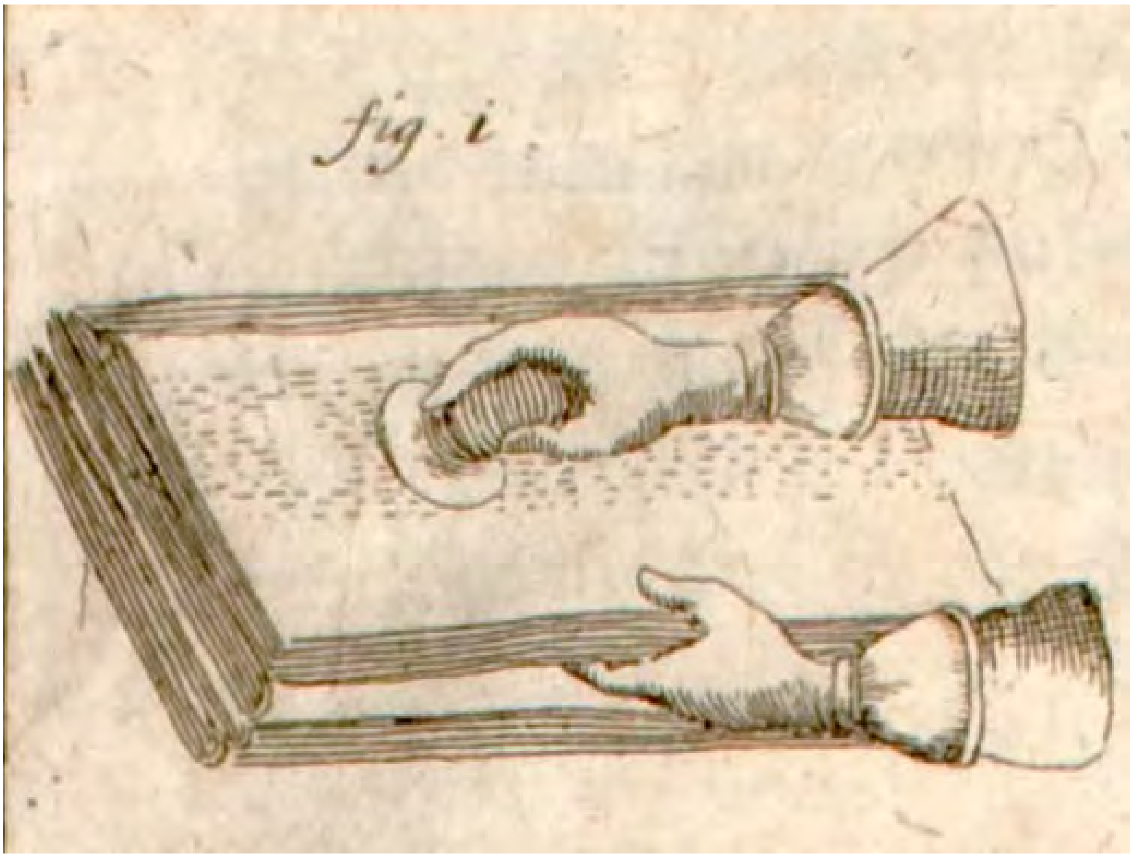

Figure 2: The exacting demands of theoreticians and astronomers included the elusive quest for a hyperbolic lens. Such a lens was sought as a solution to the problem of chromatic aberration. The diagram shows an example of manual grinding on a planar surface to produce a hyperbolic lens. The grinding for a hyperbola followed straight sweeps rather than circular motion. The lens is held by a wooden handle, called a mollette (see Figure 26). J. Zahn, *Oculus artificialis teledioptricus*, Herbipoli: Sumptibus Quirini Heyl, 1685–6, 'Fundamentum III', 'Practico-Mechanicum Fabrica', 34, Iconismus VI, fig. 1. © Whipple Library, Cambridge, STORE 43:17.

In Chapter Three the focus shifts to the incorporation of optical quality glass into a range of instruments from spectacles and burning mirrors to spy-glasses and microscopes. The history of optical instruments has been dominated by priority attributions not least because of the close connexions described in this chapter. Mobility and sociability together with networks of epistolary exchange, politics, commerce and print characterised the transmission of optical instruments and their construction through Europe. Chapter Four continues the concerns of Chapter Three, but draws the focus to England and in particular the London trade. The final section of the chapter narrates the exasperated correspondence of mathematicians Charles Cavendish and John Pell over Richard Reeve's London workshop as they chafed at the tension between demand and limitation in materials, technology and skills.

Chapter five offers detailed accounts of lens-grinding from the leading workshops, through expert amateurs, to influential publications. The performance of the lens product is shown to depend on a combination of idiosyncratic practice and high-quality material. Further, René Descartes's tribulations show how the abstract claims of theoreticians were informed by the successes, frustrations and limitations of materials and manufacture. This theme of the conceptual and social influence of optical glass and its manipulation is extended in the focus of Chapter Six: the 'intelligence brokers.' These were scientific and political correspondents who mediated the dissemination of information and whose exchanges reveal the burgeoning cultural interest in optical instruments through the early modern period. Where Chapter Six studied international networks and famous brokers for traces of optical glass, Chapter Seven focuses on London workshops as nodes that attracted the interest of a diverse array of intellectual, social and political luminaries and brought these significant figures into contact with one another. Advertising disputes reflect the importance to practitioners of this status as a hub of interest, while the inheritance of this status was entangled with the passing on of craft skill, tools and names. Chapter Eight develops the themes of Chapter Seven, status, competition and inheritance, to consider the recalcitrant problem of chromatic aberration: the coloured bands produced by the distortion of light passing through lenses which obstructed and vexed user of optical instruments (Figure 2). Chapter Nine concludes this survey with a summary of the developments described in the preceding chapters.

This work by Anita McConnell is a true survey. It contains a wealth of technical information gathered through extensive fieldwork, not just in England but across Europe, brought together here in one place. At the time of its original compilation such a survey was only possible through Anita's love of travel and her international network of friends and colleagues. When, in 2014, I was commissioned by Anita through the Whipple Museum to edit and provide images and captions for the unpublished glass monograph, it was a privilege to find that almost all of the numerous original publications referred to in Anita's text could be accessed in the Whipple Library's rare book collection (with many now also digitized online). In consultation with Anita I sought out images with a particular emphasis on the technical skills of glass working. Anita's remarkable facility for the language of mechanism meant that we were able to select images of machines and processes that likely reflect actual practice. One obstacle to such a study is that images in early modern technical accounts are often cannibalized from other works, so that the text does not correspond with the image. This was a particular frustration in the case of the 1752 illustrated French edition of Neri's *Arte vitraria* held by the Whipple Library. Once I identified that these images, and large portions of text, were carried over from Agricola's 1556 work *De re metallica*, the authoratitative 1950s translation of Agricola's original Latin by Hoover and Hoover became an invaluable resource for translating the obscure technical French of the 1752 Neri edition. It then became possible to give a detailed description of the content, drawing on Hoover and Hoover and adapted as and where the French diverged. With Anita's approval this account and the images were incorporated into her original Chapter One, to provide a useful description of the basic method of making glass from raw materials.

Many of the figures in this survey come from texts and objects held by the Whipple Library and Whipple Museum in Cambridge. It is with thanks to them, and in particular to Anna Jones, Steve Kruse and Joshua Nall that they appear here. It is hoped that their inclusion will encourage the curious to make use of these remarkable collections.

Chapter One
The implantation and transmission of European glass-working knowledge

Figure 3: View of Venice, hand coloured engraving by Bolognino Zaltieri, 1565, in G. Braun and F. Hogenberg, *Civitates orbis terrarum*, 1571–1617, Xn4, Middle Earth, CC-PD-Mark.

<u>Venetian manufacture of *cristallo* glass</u>

The European manufacture of fine glass originated in the parish of Santo Stefano, Murano. In 1291 all glass-workers were consigned to this suburb of Venice by law with the claim their furnaces posed a threat to the safety of the buildings of Venice itself. It was customary to quench the furnace fires during the summer. At first this may have been due to the availability or otherwise of fire-wood and bricks. Later, when fires were extinguished at the end of July and relit at the beginning of October, the reason given was to clear stocks, repair the furnace, and allow the master to rest.[1] A number of early Italian glass-makers' names are compounded of Bar, Ber, Bor, Me, Mi: Hebrew elements that denote origin. These were suffixed by an element identifiable as a centre of early glass-making.[2] It has been suggested that the bearers of these names were brought from the Near East during the Crusader period. The Genoese are considered to have been the principal agents for this movement, importing skilled labour to develop the manufacture of Syrian products—including glass—on their territory. From Genoa and Lombardy some families either came or were taken to Venice.

The first uses of the adjective *cristallino* in post-Roman times come in a product list of 1409 from Verona and another of 1454 from Como. In these instances, *cristallino* denoted 'like natural crystal'. The first preparation of true clear glass is attributed to members of the Barovier (or Baroviera) family of glass-makers in around 1450. Angelo Barovier, the most famous of this family, visited Francesco I Sforza, the Duke of Milan, and perhaps travelled elsewhere in Italy with his attractive wares. *Cristallino* soon came to mean 'made from artificial crystal', the material itself being known as *cristallo*. In general, natural rock crystal was referred to as *cristallo di montagna*. In 1486 the *cristallieri*, workers in rock crystal, were permitted to use glass for some of their products.[3] By 1467 such items were listed in an inventory of Charles the Bold, baptized Charles Martin and then Duke of Burgundy, and they figure in a list of 1471 from Anjou. They are mentioned in a French document of 1495, while Southampton port documents of 1481 report various crystal items shipped in a Venetian galley.[4]

The Barovier family succeeded in producing crystal by the careful selection and preparation of their raw materials. They employed crushed flint as the silica component of their glass, and the addition of manganese to decolour the melt. The transparency they achieved made Venetian glass-ware highly desirable and generated much demand for its replication elsewhere as *façon de Venise*. The glass-makers themselves soon sought to restrict the sale of crystal; their petition of 1463 resulted in 1482 in a decree limiting it to designated days and shops. The glass-works were on the tourist trail for visitors to Venice from at least 1490;[5] while the

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[1] P. Zecchin, 'La cavata dei vetrai muranesi', *Rivista della stazione sperimentale del vetro,* 25, (1995), 207–218.

[2] A. Engle, 'A study of the names of early glass-making families of Europe as a source of glass history', *Readings in glass history,* 1, (1973), 51–65. For example: the name of Angelo Barcaluso, who worked for Mansell in London in 1615, recorded as born in Venice, may have derived from Caluso, near Vercelli, the latter town perhaps seen in the name of Jacob Verzerlini.

[3] L. Zecchin, 'Cronologia vetraria veneziana e muranesi dal 1485–1490,' *Vetro e silicate,* 8, (1978), 59–62.

[4] L. Zecchin, 'Il vetro 'cristallino' nelle carte de quattrocento', *Vetro e silicate,* 7 (2), (1963), 21–24.

[5] L. Zecchin, 'Il vetro muranese negli scritti del cinquecento', *Vetro e silicate,* 7 (3), (1963), 21–

discovery of America brought gold to Europe and encouraged the purchase of luxury goods. Wealth and travel were crucial enablers to the transfer of glass-working knowledge.

The craft of making mirrors, other than of metal, reached Venice at the end of the fifteenth century. Prior to this glass mirrors had been imported from Germany. Indeed in 1318 it was a German master, together with a Muranese and two Venetians, who applied for a concession to make mirrors in Murano. The bid appears to have been unsuccessful. A Frenchman, Robert, and a Muranese glass-house owner both sought a concession in 1493. However, the first conclusive evidence of crystal mirror manufacture at Murano comes from a list of exports to Mantua in 1506. In 1507 the brothers Andrea and Domenego d'Anzolo dal Gallo announced that they had discovered how to make mirrors of *cristallo*. These were claimed to be as fine as any in the world, save those from a single German house, which were very costly. The brothers sought a privilege for twenty-five years but were granted only twenty.[6] Leonardo Fioravanti, a medical practitioner and alchemist of Bologna, devoted a small part of his *Specchio di scientia universale* (1564 and later editions) to the preparation of mirrors. Fioravanti's description explained that a long tube of crystal was blown, slit open, and the *quari*, or squares, flattened between hot iron plates. These squares were then polished like those of metal, with a sequence of increasingly fine abrasives.

Migration from Venice

The Muranese glass-workers were such assets to the Venetian state that, by the mid sixteenth century, they were prohibited from emigrating. At the same time their knowledge was so valuable that many were in fact enticed abroad by the offer of good money. A census of adults taken at the visit of the Bishop of Torcello, Antonio Grimani, in 1591 counted 4,150 glass-workers in the parish of Santo Stefano. The family names match those later recorded elsewhere in Western Europe.[7] In the late sixteenth and early seventeenth centuries they came to be employed within other regions of Italy. Important centres of glass-making developed at Altare in Liguria and at Florence. Some production also took place at Treviso, Ravenna, Vincenzo, Padua, Ferrara, Ancon and Bologna; as well as further afield: in France, the Low Countries, England and Scotland.

The first furnace in the Spanish Netherlands authorized to make crystal, *façon de Venise*, was set up around 1535 in Antwerp. At that time Antwerp was Europe's leading port and the world's marketplace. In 1541 Jean Michel Cornachini, said to

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[6] P. Zecchin, 'Gli specchi veneziani', *Rivista della stazione sperimentale del vetro,* 23, (1993), 299–306.

[7] L. Zecchin, 'In "rio dei verieri" fra il 1564 ed il 1575,' *Vetro e silicate,* 9 (1), (1965), 24–7.

be 'from Germany' but probably of Italian origin, secured a licence from the Holy Roman Emperor, Charles V of the Habsburg family; and his sister Maria of Hungary, governor of the Low Countries, to make mirrors of crystal and of steel at Hopland. The 1541 licence suggests the earlier, 1535 glass-works may have been unsuccessful. Cornachini's endeavour does appear to have established itself as he travelled back to Venice to recruit more men. On his return to Antwerp, however, he found his furnace destroyed in the wake of the assault by the Duke of Guelders' military leader, Maarten van Rossum.[8] Cornachini was connected with a following group, active in 1549; and with the successful episode from 1561 under Jacomo Pasquetti, an Italian merchant from Brescia, who described Cornachini as his predecessor and colleague. The group, which introduced crystal into Western Europe, went to Antwerp in 1549 under a licence given by Charles V to a merchant, Jean de Lame of Cremona. This authorized de Lame to set up a furnace to make crystal, in the fashion of Venice, and to bring over workmen, soda, and equipment from Italy. Of these glass-workers, eight went direct to London under contract to the crown.

The men moved from one glass-works to another. One, named Mazzoli, left Murano around 1650 and settled in London to install a crystal furnace. It may have been his production that led the mathematician John Pell to inform educational reformer and writer Samuel Hartlib in the autumn of 1653 '[i]n the Glasse-house there is a new sort of glasses very lately invented very curiously white as a pot[.]'[9] From London, Mazzoli moved to Brabant and married there. After seven years at Maastricht he found employment as a master at Rouen, from where Jean Baptiste Colbert, the comptroller-general of finances under Bourbon monarch Louis XIV, summoned him on his assurance that he was a master mirror-maker.[10] The transmission of a knowledge of crystal took place through the physical movement of craftsmen across Europe.

Outside their native region, the Muranese strove, not always with success, to convert the unfamiliar raw materials available into crystal as fine as that of their homeland. In Italian glass-making centres silica was obtained by grinding quartz pebbles found in certain riverbeds. The Muranese glass-makers used pebbles from the Ticino, an Alpine tributary of the Po, which were much sought after by other glass-makers abroad. Florentine glass-makers used similar stones from rivers coming from the Appennines. On occasion they substituted quartz from the Versilia or fragments of rock crystal in an attempt to obtain a clearer glass. The alkali employed, being often obtained from local plants, also varied from place to

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[8] R. Chambon, *Histoire de la verrerie en Belgique,* Bruxelles: Librairie encyclopédique, (1955), 87–89.
[9] **HP Eph.** 28/2/72B.
[10] F. Savorgnan di Brazzà, *Tecnici e artigiani italiani in Francia,* Roma: Libreria dello Stato, (1942), 78.

place. For Venetian crystal the preferred alkali was ashes of the maritime soda plant (whose botanical name is *salsola soda* or *salsola kali*) imported from Syria. Murano glass, being soda-rich, had a dark tint, which the glass-workers lightened with the addition of potash. Ashes from ferns growing inland were potash-rich so Florentine glass was sodium-potassic, similar to the Bohemian glass later used for optical purposes.[11]

In the Low Countries there were glass-works at Liège and Antwerp, and later further to the north. For the most part the industry relied on Italians from Murano, using the same ingredients to make potash glass which was known as Venice crystal, 'crystal' in Dutch, to distinguish it from soda glass known as 'grove glasen' or forest glass. It was with the assistance of Italians that Govaert van der Haghe of Antwerp founded the first northern works in 1581 at Middelburg. The Venetians Antonio Miotto and Simon Fabri, producers of crystal glass, succeeded him in 1605. Other crystal manufactories were established in the region. Common glass was useless for lenses. Iron contamination in the sand from which common glass was made lent a coloration that could only be partly annulled by strong heating; Venice crystal was therefore preferable. This could be obtained as 'mirror glass' or 'Venetian mirror' and was, compared to the forest glass, clear; homogenous; colourless; free of bubbles and streaks' and in general well polished by the iron. Lenses could be cut from a piece of such sheet, the practice being to draw a circle slightly oversize and trim the glass with hot pincers.[12]

In France a letters patent of 1551 granted Theseus Mutio, gentleman of Bologna, the privilege of manufacturing in France glasses and mirrors in the fashion of Venice. Nothing came of this, nor of subsequent, similar patents that were granted.[13] As early as 1585 various shops, located for the most part in Normandy, were making optical glass said to be as beautiful and as perfect as that produced in Venice. Rouen was said to have acquired a world-wide reputation for her lenses and spectacles.[14] The first statutes applicable to the guild of spectacle and mirror-makers of Rouen dated from 1538, and were augmented to take account of changing circumstances in 1639 and 1748.[15]

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[11] S. A. Bedini, 'Lens-making for scientific instrumentation in the seventeenth century', *Applied optics*, 5, (1966), 687–694, citing P. P. G. Conti, 'Il vetro per l'ottica in Italia', *Atti della Società Colombaria di Firenze*, Anno 1930–31, 36–39; and A. Neri, *L'arte vetraria ....* , (1612). See also A. Gasparetto, 'Soda and the glass-maker', *Readings in glass history,* 5, (1975), 53–56.

[12] **Beeckman**, 3, (1627–34), i–xiv and 371–431: Notes on grinding and polishing glass.

[13] M. A. Voisin, 'L'industrie verrière aux environs de Cherbourg', *Bulletin de la Société Artistique et Industrielle de Cherbourg*, 18, (1895), 31.

[14] W. C. Scoville, *Capitalism and French glass-making, 1640–1789*, Berkeley: University of California Press, (1950), 32, citing P. Pansier, *Histoire des lunettes,* Paris: A. Maloine, (1901), 59.

[15] C. Ouin-Lacroix, *Histoire des anciennes corporations d'arts et métiers,* Rouen: Imprimé par

The Venetian monopoly on fine mirror glass ended when Colbert established the Compagnie Royale des Glaces in 1665. In 1664 Colbert had asked François de Bonzi, ambassador in Venice, to bring from that republic the secrets and the artisans skilled in the two important arts of mirror and lace-making. De Bonzi said that this would be risky as Venetian regulations forbade any workman to take his craft abroad under penalty of his relatives being imprisoned and, if he stayed abroad, himself being killed. Nonetheless, some twenty Venetian workmen arrived in Paris in 1665.[16] The company received letters of patent conferring a twenty year monopoly and allowing it to establish one or more works for the production of mirror and other flat glass for glazing, as well as vessels of all sorts, throughout France. Production commenced in the district of Saint Antoine in Paris. In 1667 the company took over the mirror plate glass-house at Tourlaville, near Cherbourg, started around 1653 by Richard Lucas de Nehou, who had formerly operated a forest glass-works close to Cherbourg. Lucas's Muranese workmen shut everyone else out when blowing the plates, but their secret was discovered by the ruse of stationing some French glass-workers by the ventilation holes on the roof, through which they could watch the process. Lucas enjoyed a privilege of 1655 allowing him to make glass for spectacles, but lost this in 1667 when he was obliged to turn his production over entirely to mirror glass.[17] In 1673 and again in 1686 Colbert sent experts to experiment with the melting of optical glass and grinding lenses, hoping to improve the domestic economy at the expense of Italian and Dutch producers.[18] By 1673 French glass was better than Venetian and the government was able to prohibit imports.[19]

Early sixteenth-century English glass-works only produced domestic glass-ware. Window glass and crystal had to be imported to satisfy what appears to have been a limited demand while Venetian glass-wares had been transported to London as early as 1399. The first record of alien workmen relates to the eight Venetians who arrived from Antwerp in 1549 to set up a permanent *façon de Venise* drinking-glass manufactory, probably at the furnace near the palace of Belsize belonging to Edward Seymour, Duke of Somerset, in the reign of Edward VI of the House of Tudor.[20] Within two years all but one had returned home, perhaps frightened by

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Lacointe, (1850), 262.

[16] M. A. Voisin, 'L'industrie verrière aux environs de Cherbourg', *Bulletin de la Société Artistique et Industrielle de Cherbourg*, 18, (1895), 33 names some of these men and gives their salaries.

[17] **Arch. Nat.** E rég.778A, 63ff.

[18] P. Boissonade, *Colbert, le triomphe de l'étatisme*, Paris: M. Rivière, (1932), 60. One of these experts was Nicolas Hartsoeker, for which see Chapter Five.

[19] E. Peligot, *La verre: Son histoire, sa fabrication*, Paris: G. Masson, (1877); **Arch. Nat**. E 778A f63r–66v.

[20] A. Gasparetto, 'Le relazioni fra Venezia e l'Inghilterra nei secoli XVI e XVII e la loro influenza sulle forme vetrarie inglesi', *Vetro e silicati*, 14, 82, (1970), 16–20; 7 August 1565. The palace of Belsize lay to the north of London, in the area now known as Belsize Park.

the threats of reprisal against their families. Other proposals were aired but never seemed to materialize. Credit for establishing a permanent industry generally goes to either Jean Carré, or Jacob Verzelini, both entrepreneurial glass manufacturers whose enterprises are described in Chapter Three. By 1620 Girolamo Lando, Venetian ambassador in London, could write home:

> various Venetians including many natives of Murano now make or teach the art of making looking glasses and flint glass; one of them tells how to make curved flint glass, another how to clear it better, and English workers can now make crystal equal to that of Murano.[21]

In the later seventeenth century the production of Venetian crystal declined in quality and quantity in parallel with Venice's reduced political status. At the same time, glass-makers elsewhere in Europe improved the quality of their crystal, while in France they developed the skill of casting large mirror plates, further reducing demand for the genuine Venetian products. The rise of Bohemian crystal during this period was a further blow to the industry. After the collapse of the Roman Empire forest glass had continued to be made in Bohemia but from the fourteenth century more care was given to glass-making in the selection of the raw materials, especially quartz. Potash with a low iron content was the alkali, and manganese was the decolourizing agent. Towards the end of the sixteenth-century techniques of engraving glass with copper or bronze wheels were developed at the Prague court of Emperor Rudolph II of the House of Habsburg, by his Italian artists. These techniques had been practiced for many years both in Rome and in Germany for the decoration of natural rock crystal and the art was highly valued. The Emperor gave a patent for engraving glass in this way to Caspar Lehmann, or Leman, a diamond cutter. The art of engraving reached a peak in the seventeenth century but it was not until around 1680 that a heavy potash-lime glass was developed which resembled natural crystal and merited this elaborate decoration. The qualities of the raw material and the artistic skills of the engravers combined to produce outstanding works of art in demand throughout Europe; the Bohemian industry was able to meet this demand and to supply crystal, which would eventually displace that from Venice.[22]

Caspar Lehmann worked in the court of the Duke of Bavaria, Wilhelm V of the house of Wittelsbach. The Munich court boasted the gold and gem working skill of court-jeweller Valentin Drausch, and the stone carving of Zacharias Peltzer. It is thought that the skill of these virtuoso informed Lehmann's engraving technique.[23]

Cal. SPD Edward VI & Mary (1547–1580), 265.

[21] Girolamo Lando, Venetian Ambassador in England, to the Doge and Senate, London, 27 March 1620. **Cal. SPV.** 16, (1619–21), 212.

[22] R. W. Douglas and S. Frank, *A history of glass-making,* Henley-on-Thames: Foulis, (1972), 18.

[23] http://www.bayerisches-nationalmuseum.de/index.php?id=1 [accessed August 2016].

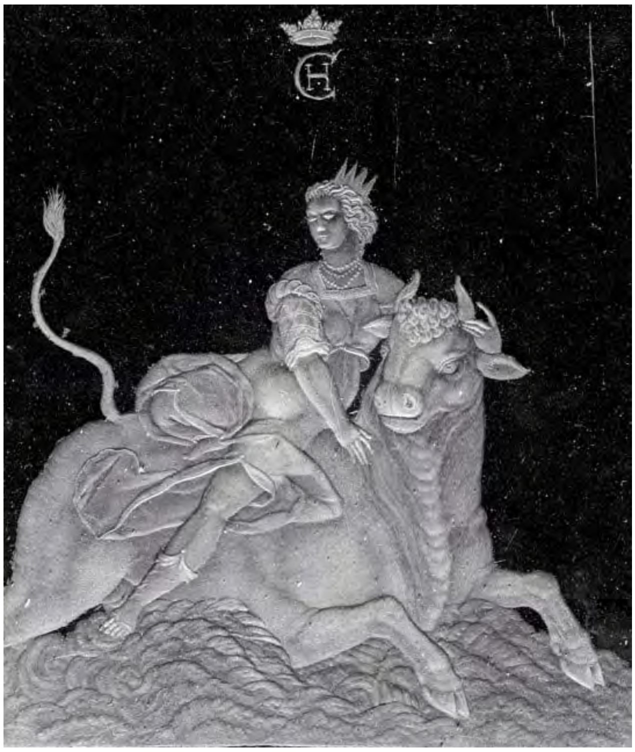

Figure 4 (left): Mountain crystal panel with singing angels, by Caspar Lehmann, 1586–88. FA2010, Bayerisches Nationalmuseum, Self-published work [by FA2010], PD-self.
Figure 5 (right): Europa and the Bull, Wheel-engraved glass panel by Caspar Lehmann, 1608, Wmpearl, Bonhams, CC-PD-Mark.

Publication of Neri's *Arte vitraria*

Despite the restrictions on the movement of skilled craftsmen, the first systematic textbook dealing with the preparation and treatment of raw materials for glass-making, together with directions for making a variety of types of white and coloured glass, was widely available in Italy from 1612. This was the work of priest and glass-maker, Antonio Neri, and titled *L'Arte vetraria distinta in sette libri, ne'quali so scropono effetti mervigliosi e s'insegnano segreti bellissimi del vetro nel fuoco e altre cose curiose*. The textbook was published in Italian in Neri's hometown of Florence in 1612, with a second impression in 1661; second and third editions were issued at Venice in 1663 and 1668; and a fourth edition at Milan in 1817.

Neri, the son of a physician, was born in Florence in 1576, entered the church, and by 1601 was a priest in the household of Alamanno Bertolini in Florence. There he met the Portuguese nobleman Emanuel Ximenez, with whom he shared an interest in chemistry and scientific matters.[24] When Ximenez returned to Antwerp he

[24] An inventory of the possessions of Emmanuel Ximenez is currently underway: http://ximenez.unibe.ch/project/ [accessed August 2016].

corresponded with Neri, and it is from Ximenez's letters alone that we can follow Neri's activities as his letters to Ximenez have not been found. By 1601 Neri was working as a craftsman in the Medici glass-house in Florence where he succeeded in making a precious stone like chalcedony, in which he was particularly interested, through artifice. Ximenez persuaded Neri to spend some time with the glass-makers of Antwerp. After two months in Pisa in the summer of 1603 working on coloured glasses in the Medici glass-house, Neri appears to have set out by the route Ximenez had advised: going first to Venice then joining a group of merchants heading for the mid-Lent Frankfurt fair. Thought to have returned in 1610 he was back in Florence by March 1611 and his *Arte vetraria* appeared the following year. He died in Florence in 1614.[25]

Neri's text was seized on by the Royal Society of London as an example of a book on a useful trade. It was translated as *The Art of Glass* and extended for publication in 1662 by Christopher Merrett a physician and writer on natural philosophy. Merrett added his own observations and views, equal in length to the original text; reviewed the opinions of older authorities and described the glass-house furnaces and tools then in use. Other translations and editions carried Neri's book across most of Western Europe. The publishing history can be summarized as follows:

Arte vetraria:
1612 in Italian. Florence.
1661 in Italian, second impression, Florence.
1663 in Italian, second edition, Venice.
1668 in Italian, third edition, Venice.
1817 in Italian, fourth edition, Milan.

The art of glass:
1662 in English, translated by Merrett with his Observations, London.
1826 in English, without Observations.

De arte vitraria, based on Merrett's edition *The art of glass*:
1668 in Latin, translated by Andreas Frisius. Amsterdam.
1669 in Latin, second impression.
1681 in Latin, translated by Andreas Frisius, second edition.
1686 in Latin, translated by Andreas Frisius, third edition.

Ars vitraria experimentalis oder vollkommene glasmacher-kunst:
1678 in German, translated by Friedrich Geissler.
1679 in German, translated with additions by Johann von Löwenstern-Kunckel.

[25] R. B. Mentasti (ed.), Introduction and notes to A. Neri, *L'arte vetraria, 1612*, Milan: Edizioni il Polifilo, (1980), XLI–LXVIII.

Frankfurt and Leipzig.
1689 in German, second edition. Frankfurt and Leipzig.
1743 in German, third edition. Nurnberg.
1752 in French, translated from a seventeenth-century German edition, with comments by Paul-Henri Thiry, baron d'Holbach, Paris.
1756 in German. Nurnberg.
1785 in German. Nurnberg.

De l'art de la verrerie, professed to be original but in effect a translation of Neri, by Jean Haudicquer de Blancourt:
1697 in French. Paris.
1699 in English, translated from the French.

Arte de videria:
1776 in Spanish.

The glass furnace

The Whipple Library, Cambridge, holds a copy of the 1752 French translation of *Arte vetraria*, based on a seventeenth-century German edition. The German source edition incorporated images and text from German scholar Georgius Agricola's 1556 work *De re metallica.*[26] Though these additions dated from two centuries before they were carried over into the 1752 French publication, and though equipment, materials and practice varied widely even among contemporaries, the diagrams and description still provide a useful account of the basic method of making glass from raw materials.

The original text accompanying Figure 6 describes how a furnace such as this, vaulted and similar to an oven, is used to melt the material components of the glass batch. The mixture was heated in the upper chamber of the furnace (B) by a fierce fire of dry wood in the lower chamber (A) until converted into a vitreous mass. If the mass was not sufficiently free from dross it was taken out, cooled, and broken into pieces (C). These fragments were then heated again in pots in the same furnace.

Furnaces were made from unbaked bricks, dried in the sun. The bricks were made of a kind of clay that could not be easily melted or reduced to powder on heating. The earthenware vessels and pots, Figure 7 (D), were made from the same kind of clay, dried in the shade. The clay for furnace bricks was cleaned of small stones and beaten with rods. The bricks were then laid with the same clay instead of lime.

[26] G. Agricola, *De re metallica*, 1556, translated by H. and L. Hoover, New York: Dover Publications, (1950), Book XII.

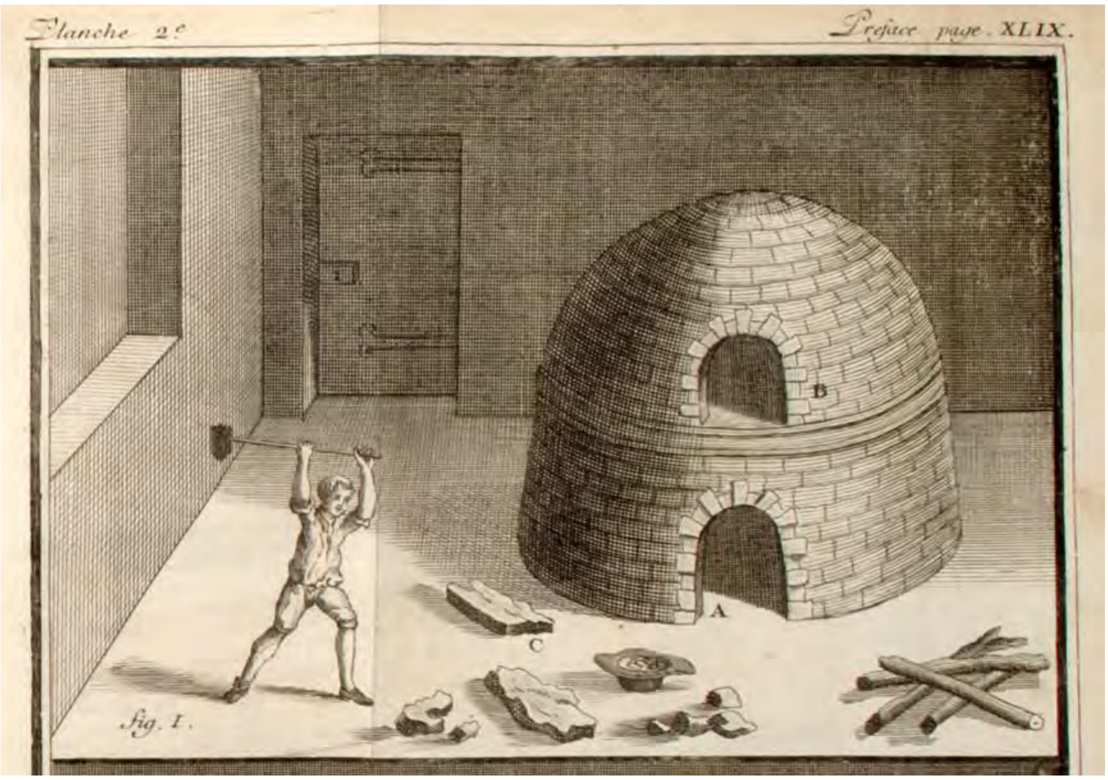

Figure 6: A. Neri, *Art de la verrerie*, Paris: Chez Durand, 1752, 'Preface', XLIX, Planche 2e, fig. I, © Whipple Library, Cambridge, STORE 35:8.

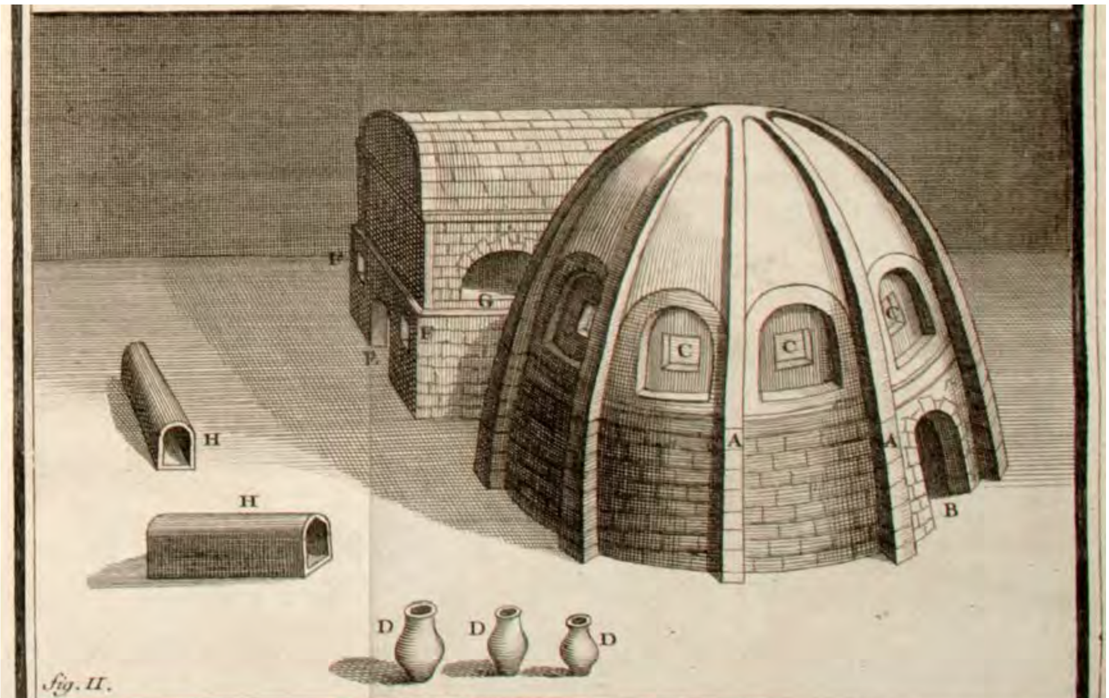

Figure 7: A. Neri, *Art de la verrerie*, Paris: Chez Durand, 1752, 'Preface', XLIX, Planche 2e, fig. II. © Whipple Library, Cambridge, STORE 35:8.

Figure 7 shows the second furnace, used to remelt the vitreous mass formed in the first. It is round and reinforced on the outside by five arches, one and a half feet thick. Like the first furnace it is divided into two chambers; the lower chamber vaulted, like an oven, and with walls one and a half feet thick. This lower chamber has a narrow mouth in the front (B), used to add wood to the hearth that forms the ground inside. At the apex of the vaulted lower chamber there is a large round hole opening into the upper chamber, so that the flames can penetrate into it. Between the arches in the walls of the upper chamber are eight windows labeled (C). Through these windows the big-bellied pots, (D), may be placed onto the floor of the upper chamber, around the large hole that connects upper and lower chambers. The thickness of these pots is about two digits, their height two feet, the diameter of the belly one and a half feet, and of the mouth and bottom one foot.

In the back part of the furnace is a rectangular hole, measuring a palm in height and width, through which the heat penetrates into a third adjoining furnace. This furnace is rectangular, eight feet long and six feet wide and, as in the first, fed by a hole in the base (E); it also consists of two chambers, of which the lower chamber is a recess (F) for oblong earthenware receptacles (H), which are about four feet long, two feet high, and one and a half feet wide. The upper chamber has two holes (G), one on each side, designed to accommodate the earthenware receptacles (H). Glass blown into the desired forms, (see stages described in Figure 9), are taken from the upper chamber, and immediately placed in these receptacles to cool under a gradual decrease in temperature. Cooled too rapidly and the glass would burst.

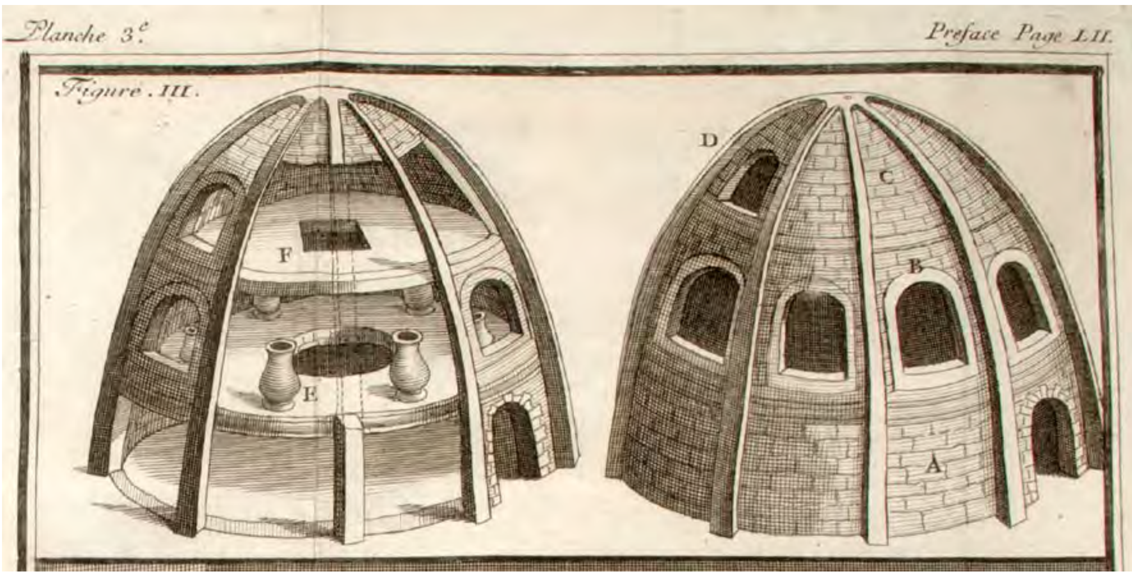

Figure 8: A. Neri, *Art de la verrerie*, Paris: Chez Durand, 1752, 'Addition', LV, Planche 3e, fig. III. © Whipple Library, Cambridge, STORE 35:8.

Practice varied and some glass-makers made use of fewer furnaces. Those using two furnaces would partially melt the mixture in the first (Figure 6), and not only re-melt it in the second (Figure 7), but also replace the glass articles there. In effect this practice did without the third rectangular furnace described in Figure 7.

Still others would use an adaptation of the second furnace, the vaulted oven described in Figure 7, to partially melt and re-melt the material, and to cool glass articles in different chambers. This did without the first and third furnace. Figure 8 shows one such adapted furnace. While it remains round, the interior is eight feet in diameter and twelve feet high, and consists of three chambers. The lowest of these, A, is not unlike the lowest of the second furnace, the vaulted oven shown in Figure 7, with a round opening E in the apex allowing heat and flame to pass through. In the wall of the middle chamber, B, there are six arched openings. Pots to be heated are placed in these openings and the remainder of the small windows are blocked up with lute. In the apex of the middle chamber is a square opening F a palm in length and width. Heat penetrates through this into the upper chamber C, of which the rear part has an opening to receive the oblong earthenware receptacles D. Glass articles are placed in these receptacles to cool slowly. On this side, the ground of the workshop is higher, or else a bench is placed there, so that the glass-makers may stand upon it to stow away their products more conveniently.

In the evening, having completed the day's work, glass-workers using the adapted furnace would place the raw material of glass, principally sand and potash, into the pots. Heating overnight would then melt it and turn it into glass. Two children would be tasked with tending the fire night and day, throwing dry wood on to the hearth. Material poured into pots in the evening was converted to a vitreous mass by morning. This fused material was then worked into glass articles and placed in the upper chamber, as in the practice described for three furnaces.

While the previous diagrams described the set up of the furnace, Figure 9 focuses on the treatment of the glass. The vitreous mass prepared from melting the raw material was broken up, while the assistant heated the second furnace so that the fragments could be remelted. At the same time the pots were exposed to a slow fire in the first furnace to warm them and drive off any moisture, and then to a fiercer heat, which fired them to a red colour. Some pots would crack and fall to pieces. The glass-makers then opened the mouth of the furnace, and, using tongs to take hold of the whole pots, quickly transferred them to the second furnace. The pots were filled with fragments of heated vitreous mass or with glass, and the windows sealed with lute and bricks, except for two little windows left free.

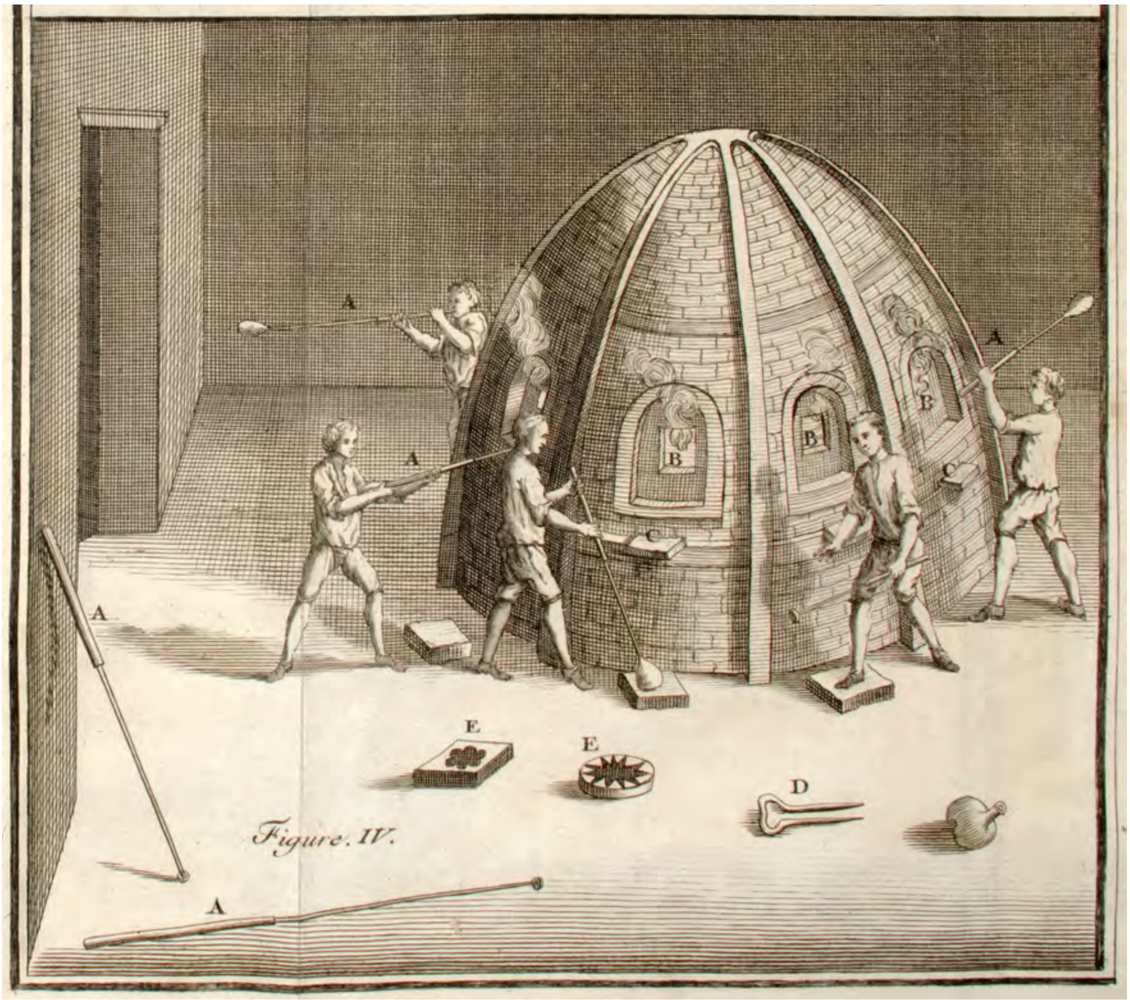

Figure 9: Antonio Neri, *Art de la verrerie*, Paris: Chez Durand, 1752, 'Addition', LV, Planche 3e, fig. IV. © Whipple Library, Cambridge, STORE 35:8.

The first of these little windows was used to inspect the glass contained in the pot; the blow-pipe rested in the second to keep it hot. When the glass was ready the hot blow-pipe was passed through the window to draw the molten glass from the pots. The text specifies that regardless of the material it is made of, brass, bronze, or iron, the blow-pipe must be three feet long. In front of the window was a marble ledge and resting on the ledge a pile of heaped-up clay and an iron shield. The clay held the blow-pipe steady was passed into the furnace while the shield preserved the eyes of the glass-maker from the fire. The glass taken up by the pipe could then be blown.

On this second melting the broken pieces of glass and vitreous mass were heated with dry wood, which emits no smoke, only flame. The greater the number of successive melts the furnace performed, breaking and heating vitreous mass and fragments of glass in cycles, the purer and more transparent the glass became with fewer spots and blisters. The quality of the product was not only dependent on the materials used, but also their treatment.

Glass-makers would use the blow-pipe to make frequent tests on the melt by drawing up the glass and observing its consistency. As soon the fragments were seen to be re-melted and purified satisfactorily, each glass-maker would use another blow-pipe, already in the pot, to slowly stir and take up the glass. Stirring further served to check the homogeneity of the melt. As the blow-pipe was withdrawn molten material would stick to it in the shape of a ball like a glutinous, coagulated gum. Taking up as much was needed to complete the desired article the glass-maker would then press the glutinous ball against the marble ledge (AAA in Figure 10) and knead it round and round until it the material binds.

When the glass-maker blows through the pipe he did so as if inflating a bubble; blowing into the blow-pipe as often as was necessary, removing it form his mouth to re-fill his cheeks, so that his breath would not draw the flames into his mouth. Twisting the lifted blow-pipe round his head in a circle, he could make a long glass, or moulding the same in a hollow copper form. Turning it round and round, warming it again, blowing it and pressing it, he could widen it into the shape of a cup or vessel, or of any other object he has in mind. The glass-maker would press this again against the marble to flatten the bottom, and mould the interior with his other blow-pipe. This done he would cut out the lip with shears, and, if necessary, add feet and handles. If desired the glass could then be gilded and painted various colours. Finally, the glass-maker laid the article in the oblong earthenware receptacle, which is placed in the third furnace, or in the upper chamber of the second furnace where there was no third furnace, for it to cool. When the receptacle was full with slowly cooling articles, he would pass a wide iron bar under it, and, carrying it on the left arm, place it in another recess.[27]

The final diagram (Figure 10) represents the glass-works furnace of Amsterdam and the associated instruments. Though not derived from Agricola, it was also added subsequent to Merrett's 1662 translation. The items illustrated are:

AAA. Ledges of marble or iron where the vitreous material is placed so that it binds after being drawn from the furnace.
BB. Mouth of the furnace, *bocca* in Italian. Used to pass pots into the furnace and draw out the melted material from the same pots.
C. A little opening called *boccarella* in Italian used to draw out a variety of glass materials.
D. Transverse wall for insulating heat and attaching *halcinelles* (E).
E. *Halcinelles* or hooks used to hang the glass-making instruments.
F. Instruments and tools used by the glass-makers such as the blow pipe, 'le *pontello* & les *spici*'.
G. Rake for drawing out cinders and coal from the furnace.

[27] *Ibid.*

H. Large copper ladle used for removing out 'la lessive', that is, lye, ash and cinders.
I. Small ladle for stirring the melted mass in the furnace and for transferring it from one pot to another.
K, L. Large and small shovels for catching the fragments of glass that fall from the blowpipe, and returning them to the pots. The smallest (marked L) is proportional in size to the opening (BB).
M. Part of furnace called *lecra* where the glasses are left to cool slowly ('bit by bit').
N. Opening or entrance of the *lecra* for passing the glass through.
O. External part of the *lecra* where the arch ends and where the glasses are put after having cooled.
P. Triangular pots used by Amsterdam glass-works.
Q. Round pots used in Harlem.
R. Pincers/ scissors (called *Tagliante* by the Italians) used to cut away excess glass.
S. Skimmer pierced by multiple holes, used to remove the alkali salt
T. Instrument (called *Borsella* by the Italians) used to open the mouth of the furnace and/or the glass vessel.
U. Instrument (called *Borsella da fiori* by the Italians) used to make flowers and other ornaments on the glass.
X. Instrument (called *Borsella puntata* by the Italians) used to stretch and bend the glass to turn/twist it like a rope.
Y. The glassmaker's blowpipe, with a wooden handle to protect the glass-maker's hands from the heat.
Z. Instrument used to make certain vessels called *urinaux.*

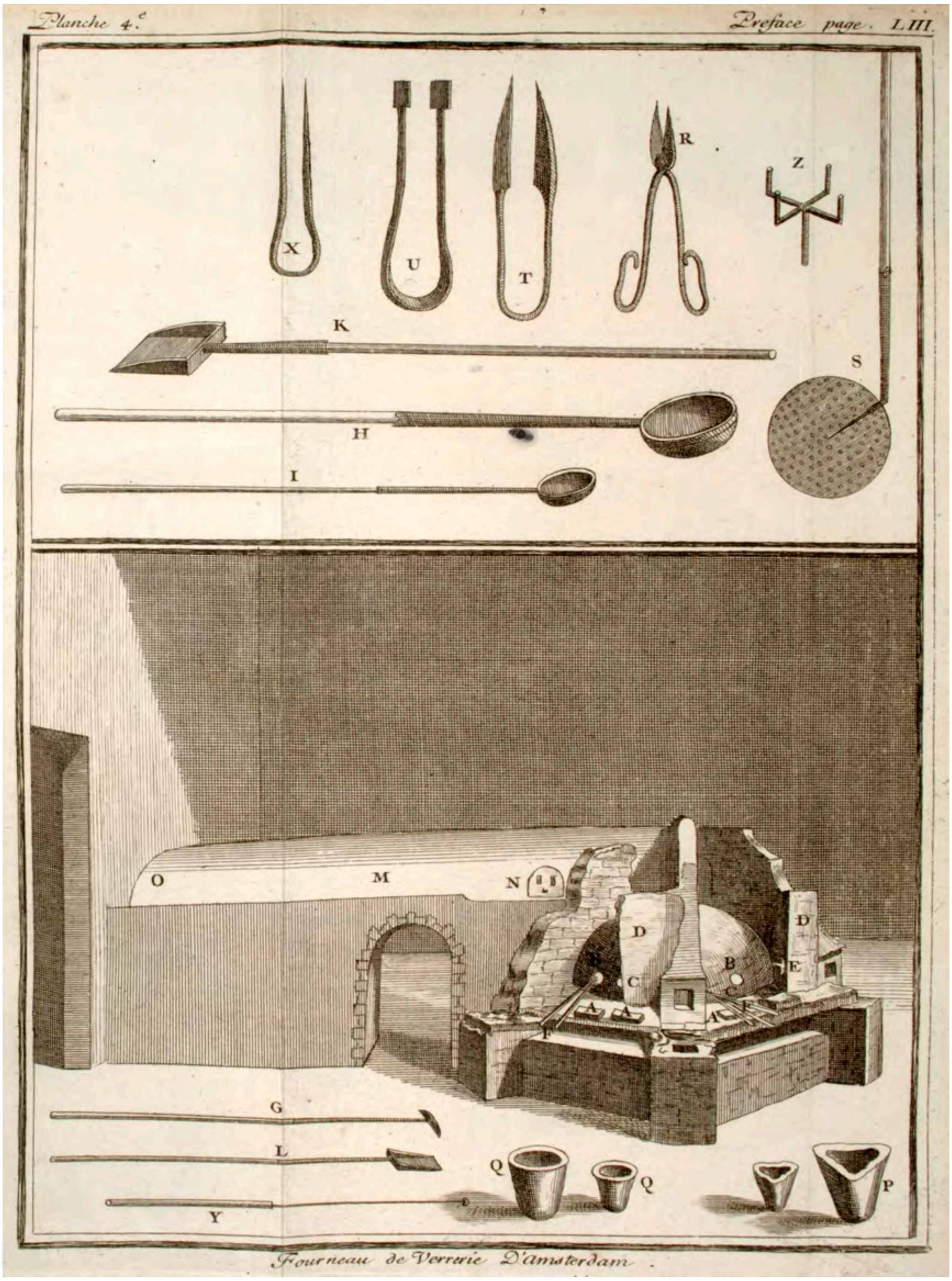

Figure 10: Antonio Neri, *Art de la verrerie*, Paris: Chez Durand, 1752, 'Addition', LVII, Planche 4e. © Whipple Library, Cambridge, STORE 35:8.

Chapter Two
The London glass-houses producing optical quality glass

Many glass-houses in Britain were limited to the manufacture of coloured wares, bottles or poor quality 'forest glass.' However it is those that produced crystal, also described as *cristallo* or flint glass, which were key to the production of British optical glass. This should not be confused with the later lead crystal, which also became known as flint, or English flint glass.

On occasion clear glass for glazing windows had been made in medieval England. Most glass-making operations were temporary affairs with furnaces were set up alongside major building projects such as cathedrals, palaces or great houses to avoid transporting such fragile material. A fourteenth-century glass-works in the Surrey Weald was an exception: established where there was a source of fairly pure sand and manufacturing window glass for transport beyond the region. The Weald works are a reminder that any successful venture was a negotiation between competing factors. For those who could afford it better window glass could be—and was—imported from Normandy.

By the mid sixteenth century only a few furnaces were active, producing a small range of vessels to serve the physician and apothecary. Imports of small value from Normandy and Flanders are listed in Port Entry Books consisting of window glass, drinking cups, spectacles and beads. As the century progressed the quantity and range of imports increased to include such novelties as hour-glasses and looking-glasses. At £1,622, imports of glass ranked thirty-fifth in the list of import values in 1565.[28] In 1567 window glass accounted for about half the total value of glass, followed by looking-glasses. Crystal tableware was imported in increasing volume.

Jean Carré and Jacob Verzelini

This demand for fine crystal and window glass encouraged some adventurers to establish manufactories in England. It was accepted that the lack of experienced native craftsmen would entail recruiting workmen from overseas. Various enterprises proposed or begun about mid century failed to establish themselves. It was only in 1567 that the entrepreneur and glass manufacturer Jean Carré may have succeeded in producing window glass and crystal tableware. Carré, who arrived in London early in 1567, was a native of Arras and had lived for some years

[28] **BL Lans.** 8.17, 'Wares brought into London, 1565'.

in Antwerp where it is thought he had been involved in the glass trade. He had adequate capital, the necessary technical knowledge, and extensive contacts with glass-makers of several traditions. His presence in London was the result of a combination of religious upheaval on the continent and personal circumstances. Carré and his family were devout Calvinists. Immediately before his arrival the 1566 religious riots in Antwerp had provoked harsh Spanish retribution and disrupted trade. Further, his favourite daughter, Mary, was married to a Flemish cloth merchant, Peter Appel, and they had been living in London since 1561. Carré brought his wife and younger children to live in his daughter's house while he organised his new venture.

Carré had obtained a royal licence to build furnaces for window glass in the Weald by July 1567.[29] His application to the crown stated that the furnaces had already been constructed and that part of his order for soda to be used in the manufacture of crystal was already delivered from Spain. He also claimed to have secured a licence from the Lord Mayor and Aldermen of the City of London to build a Venetian-type furnace for crystal at Crutched Friars in London. Whether this crystal-works ever came into being is questionable. No trace of the grant of this licence has been found amongst the City records likely to document it. The first record of a glass-maker, Peter Cant, in the parish of St Olaf-Crutched Friars, dating from 1568, is supportive. On the other hand, Jacob Verzelini, Carré's furnace master, had been in London for two years prior to this date and so could not have been brought over by Carré, as the latter claimed. Indeed, the first glass-makers linked to Carré in London (as opposed to the Wealden furnaces) are recorded in 1571, as are a group of Italian glass-workers who had arrived in June 1571 and were all entered as Carré's servants in a Return of Aliens. It is not known whether these men were gainfully employed, at Crutched Friars or elsewhere under Carré's direction.[30]

By 1568 Carré had formed a fellowship, or company, in which he held a half-interest. His partners were his son-in-law Peter Appel, Peter Briet, who was another Low Countries merchant, and Jean Chevalier of Fontenoy in Lorraine, a member of the glass-making family of de Hennezell.[31] Other members of this family worked at the Wealden glass-houses. Although his business may have been well-financed and equipped, Carré operated only under licence. He was soon threatened by the prospect of a true monopoly about to be granted to Anthony Becku, another merchant originating from the Low Countries but a denizen of London for some eighteen years. Becku and Carré contested the right to make window glass and eventually obtained a joint patent. An application by Carré and Briet for a monopoly in Venetian crystal was refused, but its production under

[29] **Cal. SPD.** Addenda (1566–79) p34; **Cal. SPD.** Eliz (1547–80), 297.
[30] A. Engle, 'Glass and the Elizabethan period', *Readings in glass history,* 8, (1977), 1–87.
[31] **BL Lans**. 59.72, 75, 76, 77.

licence from the City continued. Carré died in 1572. In his instructions for the continuation of his glass-houses, supervision of the crystal furnace at Crutched Friars was given to his brother-in-law Peter Campe.

At the time of Carré's death Verzelini was the master of this glass-house. A Muranese glass-worker, Verzelini had worked for twenty years in Antwerp where he had married and adopted the Protestant faith, before coming to London. By 1574 Verzelini appears to have bought out Carré's and Briet's interests as he claimed to own Crutched Friars furnace and be the employer of the workforce. However, still an alien and operating under a licence from the City that had been granted to the now deceased Carré, his own position remained insecure. In December 1574 he applied for and was granted the monopoly on Venetian crystal that had been denied to Carré. The terms included sole right to manufacture Venetian-style drinking glasses for twenty-one years, subject to payment of customs dues and the obligation to sell at or below the import price. Although ministers regretted the outflow of capital consequent on importing foreign manufactures, they were aware that fine crystal represented a minute proportion of such imports. Verzelini had, however, successfully implanted this craft in England and this may be the reason that his application succeeded. His skill was unchallenged and he made it abundantly clear that he could return to the continent if his patent was not granted. Although his privilege did not extend to other Venetian products such as mirrors and beads, he faced some opposition from the London shopkeepers who traded in glass-ware and resented his monopoly.

Within a year of receiving his patent, Verzelini's glass-works was devastated by fire, with the total loss of his buildings and supplies. Undaunted, he resolved to rebuild his business and applied for rights of denization papers, which were granted by November 1576. As a citizen, he was entitled to own property and he reconstructed the glass-house with a comfortable dwelling alongside. The new furnace was soon in full production, the workforce reinforced by new recruits from Murano. Throughout his long life Verzelini—or 'Mr Jacob' as he was familiarly known—was a recognized member of the London business community. There is little mention of his monopoly in official records. This implies he was able to deal with any infringement of his rights without calling on the powers of government. Further, there is no record of Venetian glasses or *façon de Venise* wares being imported, which suggests he was equal to fluctuations in supply and demand. Until the policy of the Crown changed in 1592 Verzelini and his Muranese workforce prospered almost unchallenged.[32]

In February 1592 soldier and courtier Sir Jerome Bowes was granted a patent to

[32] A. Sutton and J. R. Sewell, 'Jacob Verzelini and the City of London', *Glass technology,* 21, (1980), 190–2.

make glass as a reward for his loyalty. Bowes knew nothing of glass-making and had no intention of learning the practicalities. His interest was to control the lucrative crystal factory at Blackfriars belonging to Jacob Verzelini. Bowes's patent was a reversion of Verzelini's. It would take effect when Verzelini's patent expired in December 1595 and run for twelve years. Under its terms, import of crystal drinking glass was forbidden. That was unless Bowes could not satisfy the market, when nobles and members of the Privy Council could bring in glasses from abroad. This provision suggests some doubt in Bowes's ability to meet demand and further that only persons of quality bought crystal glasses.

Figure 11: Portrait of Jerome Bowes, oil on canvas, 1583. Flickr: Jerome Bowes, Elizabeth I's ambassador to Russia, Collection of Earl of Suffolk and Berkshire, Charlton Park, Wiltshire, CC-BY-2.0.

In March 1596 Bowes rented part of the former Blackfriars Monastery, possibly adding a warehouse the following year. Meanwhile Verzelini's sons continued to make glass at Crutched Friars, staffed by their trained Italian workmen. In addition, the Verzelinis obtained an injunction to block Bowes's enterprise. It seems Bowes was hindered by these operations and may not have succeeded in producing much glass. To advance his business, Bowes approached two city men: William Turner and William Robson. Neither man was connected to the glass-making trade. Together they liberated the patent and at considerable expense pacified the Verzelinis. It is unclear whether they played any part in the subsequent incarceration of the Verzelinis on unrelated matters.

A new furnace was built at Blackfriars, the Verzelini workforce was hired and by 1601 business was flourishing. In 1601 the patent was extended but Robson immediately found himself facing a torrent of litigation over various aspects of the patent—the right of confiscation, the prohibition of importation, and other clauses. In 1605 Turner departed to involve himself in a Yorkshire alum works, leaving Robson in charge. In 1608, before these cases were concluded, Sir Edward Salter began producing crystal from a new furnace at Winchester House in Southwark, staffed by recent arrivals from Murano. Salter was the son of a grocer, a trained lawyer, a politician and carver in the Royal Household. Arguments over his glass production in 1609 reveal that Southwark house were making true *cristallo*. Although Salter appears to have won the court dispute he ceased manufacture soon afterwards. By 1610 Robson controlled the crystal market, without needing to take over the Winchester House furnace. His output was of good quality and some Englishmen were also being trained. His success, however, depended on Crown support. From the late sixteenth century the state used restrictions and privileges to push a shift from wood to coal-burning production. In this environment Robson lost the support of the Crown and his domination collapsed.

After Salter's retirement from glass-making Sir Edward Zouch, promoter of the coal fired furnace, began production of window glass at Winchester House, adding crystal in September 1612. From this time relations between government officials, holders of privileges, and the Glaziers' Company were fraught as they debated the merits or otherwise of glass-making patents and monopolies. By 1614, the disputes finally subsided, the fire in Blackfriars furnace had been extinguished. New crystal glass was available in London from at least 1567; old crystal from an earlier period. Yet there was no mention of glass used to make spectacles, which still figured on the lists of imports.

Sir Robert Mansell's monopoly

Sir Robert Mansell, a former seaman and speculator, joined Zouch's company in 1615. He would dominate glass-making for the next quarter century. Zouch held a patent from 1614, renewed in 1615 to include Mansell's name, which gave him a total monopoly for twenty-five years. The terms of the patent required furnaces to be fired with coal and banned importation. Significant obstacles to making crystal in coal fired furnaces had been overcome by 1612. Hard Scottish coal was burned, its high price being absorbed in the prices charged for crystal wares, but little was produced in the early years. After a new window glass furnace was built at Lambeth in 1613 more of the Winchester House output was devoted to crystal. Mansell also began making mirror glass plates at Winchester House, probably using the skills of Nicholas Closson, a mirror maker from Amsterdam and a Venetian, Vincent Serino, assisted by several English workmen. The Venetian ambassador reported Mansell's success to the Doge and Senate of Venice. These authorities heard that many Muranese were employed in England, teaching Englishmen the art of making mirror glasses and flint glass, and producing crystal to equal that from Murano.[33] One such man, Giovanni Maria dell'Acqua, brought by Mansell from Venice, worked for Mansell for two years, when, ‘on some discontent’, he took up an offer to run a glass-works in Scotland. By 1620 dell'Acqua had returned to London.[34]

[33] On 27 March 1620. **Cal. SPV**. 16, 212.
[34] 20 January 1620. **Cal. SPD.** James I (1619–23), 114–5.

In 1620 Mansell was obliged to return to sea for a year. Following the death of his first wife he had married his former mistress, lady-in-waiting to the Queen, Elizabeth Roper. She was a smart and resourceful businesswoman who fought for and ably defended Mansell's rights during his absence at sea. Amongst the affidavits and petitions are documents from consumers and purchasers of his glass. Of these, the apothecaries objected to the high price of his wares, but the glaziers and the spectacle-makers came down firmly on his side. Their petition has been lost, but it was recorded that they were satisfied with the price, quality and supply of the crystal plates from his furnaces, which they then ground into lenses.[35] Many patents were reassessed and a number of them were abolished in the face of rivals and owners of glass-houses elsewhere in the kingdom. Though Mansell's survived, he had to tolerate the import of glass from Scotland. At the same time, other merchants began to import glass from Venice, including mirror glass plates. Mansell's business does not seem to have suffered, judging from the large amounts of barilla he was importing, a form of soda employed only in the manufacture of crystal.

By 1622 Mansell had petitioned the Privy Council to settle the terms of his patent forthwith. The Council referred the business to a committee consisting of the four Glass Commissioners: two Scottish lords, Ludovic Stewart, 2nd Duke of Lennox and James Hamilton, Marquess of Hamilton; and two English lords, Thomas Howard, Earl of Arundel and William Herbert, Earl of Pembroke; together with the Lord Treasurer Lionel Cranfield, and the Chancellor of the Exchequer Sir Richard Weston. In February 1623 they reported in Mansell's favour, and in May 1623 he was granted a new patent.[36] By its terms Mansell controlled the production of glass in England. However, there was no prohibition on imports and once again glass of all kinds was brought in from Scotland, France, Flanders and Venice. Besides the commercial glass-houses we also hear of the experiments of the Low Country inventor and mechanical engineer Cornelis Drebbel.[37] Commissioned by Henry Stuart, Prince of Wales, Drebbel was seeking a recipe to make glass as good as rock crystal for a telescope. However, he failed in this attempt and was obliged to use natural crystal for this purpose.[38]

Mansell's greatest interest lay in improving and expanding the production of crystal plates for mirrors and spectacles.[39] In his 1624 petition he wrote:

Looking glasses and spectacle glass plates are likewise made by me in

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[35] House of Commons Debates, 1622 **ii**, 366; **iii**, 256.
[36] 5 February 1622/3. Acts of the Privy Council (July 1621–May 1623), 329–330, 406–7; **Cal. SPD**. 14/162 N°261 B.
[37] For Drebbel's part in the history of the microscope see Chapter Three.
[38] N. Fabri de Peiresc, [Life of Drebbel], Bibl. Inguim.: Peiresc 1776, f.411v.
[39] **Cal. SPD**. 14/162/231 B, 1624.

> England, being undertaken and perfected by me with great charge and hazard, and the expense of twenty years' time, which work I did the rather undergo in that I understood the state of Venice had restrained the transportation of that commoditie rough and unpolished upon pain of confiscation and other heavy punishments in respect to the grinding, graving, polishing and foyling thereof doth imploy great numbers of poor people and afford them maintanance, which benefit doth hereby redound to the natives of this Kingdom. [40]

Mansell's claim to be concerned with the glass business for twenty years were exaggerated. Nonetheless he was by this time supplying glass for a domestic spectacle making industry. The numbers involved in that industry were sufficient for a Spectacle Makers Company to receive its charter in 1629. Mansell had to pay a high price for his achievements, recruiting and transporting Italian workmen and paying bonuses for training Englishmen. He also recruited glass-finishers from the Low Countries. One such, James Howell, went to Venice to learn about procedures and report back to Mansell.[41]

After 1630 Mansell enjoyed a decade of moderate prosperity. He invested heavily in the improvement of his looking glass plates and recruited more finishers to cope with the increased output. He met the demands of the English market in respect of his various types of glass, including that for spectacles, to the extent that he had the capacity to develop a small export trade. In 1641 fresh petitions against Mansell's patent were received and in 1642 Parliament formally abolished it, bringing Mansell's prosperous decade to a close. It is not clear what happened at the Broad Street glass-works but glass-making of one sort or another continued to flourish in London. Mathematician John Pell reported to the educational reformer and his one time employer Samuel Hartlib in 1653 that 'In the Glass-House there is a new sort of glasses very lately invented very curiously white[.]'[42] Such a comment might indicate a particularly clear product. However, it was 1656 before Hartlib learnt that '[t]here is a new art in Italy found out of casting and moulding of rock crystal out of which all vessels glasses etc etc will be made. One of Mr Boyle's friends hath the way but will not part with the secret.'[43] Mansell died in 1656. Following his death his wife Elizabeth was granted letters of administration over his estates. In 1661 clergyman and natural philosopher John Beale remarked on the dearth of fine glass available noting 'ye best glass for perfect perspectives is hardly now

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[40] Robert Mansell, 'The true state of the business of glasse of all kinds[,] I James 21,' *Thomason tracts,* 1624. [**BL.**669.f.4(7)].
[41] J. Howell, *Epistolae ho-elianae, familiar letters domestic and forren*, London: Printed for Humphrey Moseley, (3rd ed., 1655).
[42] **HP Eph.** 28/2/72B.
[43] **HP Eph.** 19/5/61A.

obtainable in London or Venice, their first care being degenerate.'[44] In the wake of Mansell's death such comments indicate the close relationship between the glass-house master's skill and the quality of traded glass.

In Mansell's day the manufacture of mirror plate entailed blowing a cylinder that would then be cut and rolled flat. The casting of plates had long been known in Venice and Nuremberg, but only small sizes could be made by this method. In 1676 the French comptroller-general of finances, Jean Baptiste Colbert, sought to encourage the promising methods of casting plates then coming into use in Normandy. A patent was granted in 1688 and, by the 1690s, large thick plates over six feet long were produced. With government backing, a flourishing home and export trade developed. An English patent granted in 1691 was barren and although some fine mirrors did emerge from the Vauxhall glass-works there was insufficient capital to expand and production lapsed. During the second half of the eighteenth century French imports increased and in the 1770s steps were taken to reintroduce cast plate manufacture in England. The British Cast Plate Glass Manufacturers' Company was incorporated as a joint stock company, and recognizing the need for cheap fuel supplies and adequate floor space, built their works near St Helen's in Lancashire.

At the Restoration the reversion of Mansell's patent was eagerly sought. Patents were still awarded to court favourites, although they were now restricted so as not to monopolise an industry. The glass-making patents were issued to nominees of George Villiers, second Duke of Buckingham. Despite the secrecy surrounding the grants, it was soon known that he controlled the manufacture of crystal plates and glasses. There was considerable animosity towards predatory courtiers. However, no opposition was raised in this instance, perhaps because his products were destined for the luxury trade rather than the general population, and because they improved in quality and fell in price under his monopoly.

On 12 August 1663 a petition from Bryan Leigh 'to make looking glasses and crystal from flint' was referred to the Attorney General who endorsed it 'something of the sort having been passed to the Duke of Buckingham [George Villiers].' Further, a patent was granted to London merchant Thomas Tilson on 4 September 1663 for similar glass. In 1664 there was a proclamation

> prohibiting the import of looking-glass plates, spectacles, burning glasses, tubes or any and other glass plates after 10 September 1664, in order to encourage the manufacture thereof by inventors who have brought it to perfection and who undertake to make it as cheap or cheaper than

[44] Beale to Hartlib, 17 February 1660/1. **HP Letters** 67/22/7B–8A.

formerly.[45]

Imports would seem to have continued, for contemporary accounts indicate that by the early 1670s Villiers's plate glass competed effectively with that from Venice. However, his drinking glasses fell short of the clarity, strength and fine design of the Venetian products. By 1674 he was facing competition from other domestic furnaces.

On 17 December 1674 the spectacle-maker Charles Woolstonecraft complained to the Court of Aldermen of the City of London that,

> notwithstanding a statute made in the reign of Queen Elizabeth requiring that any of the company should get into their hands any quantity of glass they should sell and distribute the same to and amongst their society at reasonable rates, one [not legible] and one Ratford, members of the said company, have gott into their hands the whole store of glasse, for which by combination with the Master and Wardens of the said company they demand of [Woolstonecraft] the most excessive rates[.][46]

The complaint indicates a scarcity of optical quality glass at this point in 1674–5. In January the Master and Wardens of the Spectacle-makers appeared before the Court and claimed that a by-law of their company justified their action. They were required to bring evidence to the Court, but unfortunately there is no further record of proceedings.[47]

George Ravenscroft and the invention of lead crystal

The third quarter of the seventeenth century witnessed a shift from a British glass industry that struggled to imitate the quality of continental products, to one that dominated the market with qualitatively different, superior products. George Ravenscroft has long been credited as central to this change.[48] Born into a Hertfordshire Catholic family, George and his brothers were educated at Douai College, and George then established himself as a merchant in Venice where he traded profitably for many years. Besides lace, currants and other Venetian and Levant commodities, Ravenscroft had been supplying mirror plates and coach glasses to London. In June 1674 the Venetian ambassador Girolamo Alberti, suspicious that Ravenscroft might be intending to open a furnace in London,

[45] **Cal. SPD.** Charles II (1663–4), 186, 246, 266 and 650 citing Proc. Coll., 169.
[46] **CLRO.** Repertories of the Court of Aldermen, Rep.80, 57 a and b.
[47] **CLRO.** Repertories of the Court of Aldermen, Rep.80, 69b. The Minutes of the Spectacle-makers' Company is equally silent on this affair.
[48] This section draws on C. MacLeod, 'Accident or design? George Ravenscroft's patent and the invention of lead-crystal glass', *Technology and culture*, 28, (1987), 776–803.

complained that he was recruiting Venetian glass-makers. Ravenscroft applied for a patent on 8 March 1674 and it was issued two months later. He did not seek to take over the production of crystal glass-ware, which was in the hands of other manufacturers who would undoubtedly have objected and as Villiers theoretically retained the monopoly, the law officers scrutinised Ravenscroft's application with some care. Ravencroft's petition shows:

> he had "attained to the art and manufacture of a particular sort of Crystalline Glasses resembling Rock Cristall, not formerly exercised or put to use" in England, and requested letters patent for the sole use "of the said manufacture of cristaline glasse for drinking glasses (all plates for looking glasses and such wares already patented to be excepted. As likewise other sorts of glasse of ancient fabrick, at present and for many years practised or any other sorte of glasse that shall be made by others really different from this of Your Majesty's Petitioner).[49]

He asked for a term of seven years, half the normal term. In this period it was unusual to investigate petitions. Nonetheless, in the light of Villiers's monopoly, the Attorney General Francis North undertook the procedure with Ravenscroft's claim. North declared the glass not only to be made from other ingredients, but to be finer than that from other glass-houses in England and equal if not surpassing those imported from France and Venice. The claim to have made a different type of glass was reiterated in Ravenscroft's contracts with the Glass Sellers' Company signed in 1674 or early 1675 and again in 1677. It appears that he had set up a furnace in the Savoy precinct of London to make this fine crystal, under the control of two master workmen.[50]

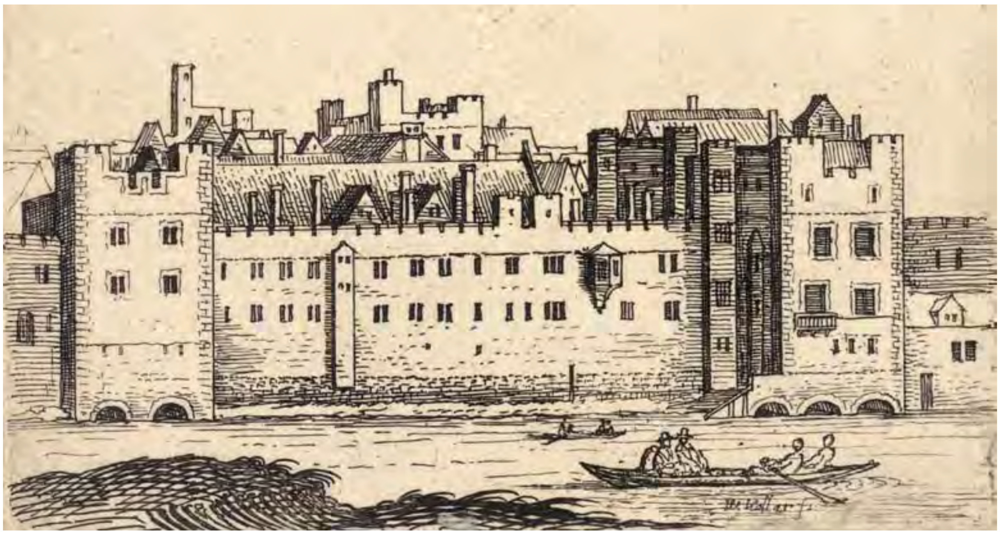

Figure 12: Etching of the Savoy by Wenceslas Hollar, 1650. Dcoetzee, University of Toronto Wenceslaus Hollar Digital Collection, CC-PD-Mark.

[49] PRO 2P29.360, 222, in *ibid.*, 789, ft. 37.
[50] *Ibid.*, 790.

A certain secrecy surrounds Ravenscroft's early productions, but from comments made by Alberti to his Venetian masters we learn that the glass was brilliant, ‘very white and thick, in imitation of rock crystal’ but also ‘soft, fragile’. This description corresponds with lead crystal, the fragility being perhaps a reference to its liability to crizzle: a process where the surface of the glass would roughen and flake. This tendency to crizzle was the problem that beset Ravenscroft in his early years. It may have been due to an excess of alkaline salts in proportion to the crushed flints, or to insufficient lead oxide to stabilize the flux of nitre, tartar and borax. The glass absorbed water from the atmosphere, resulting in chemical attack and deterioration. When the lead content was raised to 15 to 30 percent the glass became more stable. In 1676 Ravenscroft opened a furnace at Henley on Thames under the management of trained glass-maker Hawley Bishopp, for the purpose—it has been suggested—of carrying out his experiments to cure this defect without the risk of being spied on. There were reports of his process, most famously by naturalist and antiquary Dr Robert Plot in his *Natural History of Oxfordshire* (1676). Plot makes no claim of having visited the glass-house, and may not have done so, but does claim to give an account of Ravenscroft’s recipe.[51]

Ravenscroft's Savoy glass-house had some prestigious visitors. The natural philosopher Robert Hooke noted in his diary that he and the architect Dr Christopher Wren went there on 29 July 1673. The two men ‘[s]aw calcind flints white as flower, Borax, Niter and tarter, with which he [Ravenscroft] made his glasse he denyd to use arsenick he shewd pretty representations of Agates by glasse etc’.[52] Glass with a high proportion of lead oxide had long been used to make artificial gemstones, but Hooke and Wren were apparently unaware that Ravenscroft's process involved its inclusion in the crystal mix.

Trade networks, material resources and capital, together with individual human skill, all informed the development of the lead-crystal process. An emigrant Italian, probably Seignor da Costa a Montferratees, whose name referred to the glass-making centre of Altare, in the Duchy of Montferrat, approached Ravenscroft through his links with Venetian glass merchants. Da Costa had established a glass-house at the Savoy some time before July 1673. There he had begun to make a glass in which lead oxide was a major ingredient, possibly with a view to producing artificial gems. Ravenscroft put up the capital either to buy out da Costa or, more likely, to enter into partnership with him, and cemented the deal with a patent and an agreement with the Glass Sellers. In the summer of 1674 some of the drinking glasses were found to crizzle. Ravenscroft's glass-houses continued to produce glasses of traditional materials while he used his second glass-house for experiments with the lead mixture. By 1675 he believed that he had resolved the

[51] *Ibid.*, 797.
[52] R. Hooke, *The diary of Robert Hooke MA, MD, FRS, 1672–1680,* H. W. Robinson and W. Adams (eds.), London: Taylor & Francis, (1935).

problem.[53]

In 1678 Ravenscroft decided to terminate his agreement with the Glass Sellers as from February 1679. His Will, drawn up in February 1681 shows that he had by then relinquished all control over the glass-houses. It seems that during the last five years of his life Ravenscroft returned to the plate glass industry, manufacturing or importing plates for mirrors and coach windows. Hawley Bishopp had taken up management of the Henley furnace under Ravenscroft in 1676. Together with contributions from thirteen glass sellers Bishopp was able to raise sufficient capital to take over the Savoy glass-house in February 1682, for making 'crystelline or flint glasses.'

Two other houses began making flint glasses in about 1684 and by this time, 'flint glass' had come to denote lead-crystal. When pharmacist and author John Houghton surveyed the trade in 1696 he counted nine in London, four in Bristol, five in Stourbridge and others elsewhere in the country. Their output expanded in line with fashion. The earlier twisted and coloured decorative styles of *façon de venise,* for which lead crystal was unsuitable, gave way to plain sturdy shapes.[54] Lead crystal glass was not of itself suitable for lenses. Being denser, rays of white light passing through it were dispersed into a wider spectrum of colours than common glass a characteristic that gave rise to its brilliance. Lead crystal, though its clarity made it attractive for hand lenses, threw even more chromatic rings round the image than non-lead glass. It only came into advanced optical use as a component of the compound achromatic lens, as explained in Chapter Eight.

By 1696 Houghton could report 'We are of late greatly improved in the art of glassmaking for I remember the time when the Duke of Buckingham [George Villiers] first encouraged glass plates and Mr Ravenscroft first made the flint glasses.' Nevertheless, in 1694 a quantity of glass of various sorts was imported to London, including one hundred and six gross of looking glasses from Germany, eight gross from Holland; and four-dozen prospect glasses from Holland.[55]

<u>The London crystal glass-houses</u>

In the late seventeenth and early eighteenth centuries the London glass-houses delivering optical quality glass, that is, at this point, crystal without lead, were as follows:

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[53] C. MacLeod, 'Accident or design? George Ravenscroft's patent and the invention of lead-crystal glass', *Technology and culture*, 28, (1987), 776–803, on 792 and 798–800.
[54] *Ibid.*, 801–2.
[55] J. Houghton, *Collection for the improvement of trade and agriculture*, No. 196, 2 May 1696.

Broad Street: Operated by Sir Robert Mansell and patronised by the optical instrument maker Richard Reeve, who obtained glass from Broad Street for the lenses of mathematician Sir Charles Cavendish etc.

Whitefriars: First dated to 1709–11, then closed until the next house erected in 1733 by a Captain Seal. Various members of the Seal family continued until the death of Anthony Seal in July 1758 when it was sold. Thereafter the names of Hopton & Stafford, Carey Stafford, Hall & Holmes, are associated with it.

Minories: Located on the south side of Goodman's Yard at the boundary between St Botolph, Aldgate and St Mary Whitechapel. Minories made crystal glass and bottles. It was subject to a lawsuit, which revealed the names of the interested parties. Before 1651 the glass-works belonged to Sir Bevis Thelwall. After 1651 it operated under Robert Batson and Edmund Lewin, who sublet to a working partnership including John Walker. In 1678 Michael Rackett ran the works, till 1691 when he assigned his interest to a company of glass-makers. There is no further information till 1738 when the Riccards family appear to have ownership.

Salisbury Court: A flint glass-house, possibly the same visited by the naval official and diarist Samuel Pepys visited in 1669. Having fallen into disuse it was announced as operating again in 1684.

Savoy: Several glass-houses operated in this London precinct; one was set up by George Ravenscroft in 1673 and passed to Hawley Bishopp in 1675. Another was mentioned in 1683 as in the possession of Henry Holden, the King's glass-maker.

Bear Garden: On Bankside. The house where crown glass was first made. Probably active from 1678 under John Bowles, a trained glass-maker previously associated with the Duke of Buckingham, George Villiers. From 1703 it made plate glass, its eight proprietors managing to stifle all competition. Crown glass was sold by the case of ‘tables.' A table was a sheet averaging three to four feet across. A case usually contained twenty-four such sheets, but varied from house to house.

Vauxhall: Glass-house belonging to the Duke of Buckingham, George Villiers. Vauxhall was operated by workmen brought from Venice managed under their foreman, one Rosetti who was purportedly the descendent of a Venetian brought to Britain by Villiers. The works eventually came into the ownership of John Dawson, who had been an apprentice at Villiers’s works; and John Bowles, see Bear Garden. With their successors the two men ran it for most of the eighteenth century. In 1733 they decided to establish a cast plate process emulating that of the French Compagnie Royale des Glaces. An Act of Parliament was needed to incorporate this major undertaking—the new factory was built at Ravenhead in Lancashire and the first glass was cast in 1776.

Lambeth: Henry Oldenburg, German-born scientific correspondent and secretary to the Royal Society, sent glass from Lambeth to Huygens in the Low Countries in 1670. John Gumley started his own glass-house in Lambeth in 1709 and nine years later was in partnership with James Moore. Gumley and Moore served as cabinet-makers to George I of the House of Hanover, with a particular expertise in glass and the manufacture of mirrors.

Ratcliffe: No longer operating by c.1770.

Opticians who are recorded as owing money to Whitefriars glass-works at the time of Seal's death in 1758 included Jeremiah Sisson, John Cuff, George Sterrop, James Ayscough, Benjamin Martin and Edward Nairne.[56] Under the succeeding management, the same opticians continued to purchase glass there, as did Robert Banks, John and Peter Dollond, Samuel Johnston, Nairne & (Thomas) Blunt, William Parker, Jesse Ramsden, George and Thomas Ribright and Francis Watkins.[57]

Shortages and inconsistency in the eighteenth century

Despite the numerous crystal glass-houses operating in London, opticians were not always able to procure glass fit for lens-making. The epicure and writer William Kitchiner wrote in 1815 with reference to the achromatic telescope,

> Messrs Dollonds… informed me, that between the years 1760 or 1765, they met with a pot of uncommonly fine pure flint glass; crown glass was also then to be had of a much superior quality than they have been able to procure since the cessation of the glass-house at Ratcliffe[:] they could not, even then, with these confessedly superior materials, produce object glasses of larger aperture than three inches and three-quarters: such was then, when it was much more plentiful than it is now, the extraordinary rarity of good glass of so large a diameter and of the thickness required[.][58]

In January 1774 the Portuguese natural philosopher Jean Hyacinthe de Magellan,

[56] London: Guildhall Library, MS 5745A, Seal papers.
[57] Museum of London: Whitefriars Glass-house, trading ledgers, 1778–1792.
[58] W. Kitchiner, *Practical observations on telescopes*, London: S. Bagster, (1815), 62–3.

otherwise known by his Portuguese name João Jacinto de Magalhães, wrote from London to the Swiss astronomer Jacques-André Mallet at Geneva, informing him that the house of Dollond, London's leading opticians, was unable to progress the telescope he had ordered for want of good flint glass for the objective.[59] On 31 March 1775 Mallet was still waiting for his telescope, the reason being that Dollond had been obliged to suspend production. When by chance a good piece of glass was available, this could cost £100, and was one reason why Dollond had recently raised the prices of his telescopes. In September the same year it was reported that there was a great scarcity, indeed a total lack, of good glass, and by October Magellan was explaining that there would be none until the glass-makers recovered the skill of making it.[60]

This unsatisfactory situation persisted. Unpredictable results were a significant problem. However, the frustrated correspondence of astronomers and diplomats reveals that the erratic supply was not just the result of ill-defined materials or process, but also a consequence of the close state control imposed on glass production. In 1787 Hans Moritz von Brühl, the Saxon ambassador in London and himself a passionate amateur astronomer, wrote to Barnaba Oriani, an astronomer at Brera Observatory in Italy. In his letter von Brühl hoped the reflecting telescope of fellow astronomer, Sir Frederick William Herschel, would prove more successful than optician Jesse Ramsden's search for a piece of glass to make a twelve-inch objective lens.[61] In July 1788 Magellan was writing to Dom L. Garrellon, Prior of the monastery of Molême in France,

> I shall have no problem in sending you the two types of glass you desire. But it is their quality that causes me problems. This morning I learnt that Ramsden had bought 900 pounds weight of flint-glass some little time past, without finding a single piece capable of service in a telescope of 30 inches focal length! After having written the above lines, I spoke with a craftsman who works these achromatic objectives and he showed me one such, where after shaping it, he found a line or vein within it, which spoilt everything.

A month later Magellan was able to write again to Garrellon,

> I have succeeded in obtaining from Dollond the supplies of flint and crown glass for ten guineas. This is the sole source at present, for only he has permission from the revenue to remelt glass in order to clarify it.[62]

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[59] Letter, J. H Magellan to J. A. Mallet, 22 January 1774. **Geneva BPU**, MS supp. 1654, f.25.
[60] Letters, J. H. Magellan to J. A. Mallet, 31 March 1775, 1 September 1775 and 13 October 1775. **Geneva BPU**, MS supp. 1654, f.35, f.40, f.43.
[61] Von Brühl to Oriani, 25 March 1787. **Brera**, scientific correspondence.
[62] Letters, Magellan to Garrellon, 22 July and 26 August 1788. American Philosophical Society. I am obliged to Professor R. W. Home for a sight of these letters.

Magellan explained to Garrellon that the English revenue officials were empowered to levy duty each time a crucible was put into the furnace. This imposition, and the consequent reluctance of glass-makers to purge their glass of the threads and cloudiness which rendered it unusable for opticians, led to its shortage.

In 1849 the glass-maker Apsley Pellatt wrote that:

> For many years subsequent to the time of the celebrated Dollond, English Flint Glass was almost the only heavy glass used for telescopes both at home and on the continent. It was generally made from the usual mixture of Flint Glass, with about 10 per cent. increase of lead, but still more often of the ordinary mixture (of lead and other materials), and of the specific gravity of about 3.250 to 3.350.

The specific gravities given by Pellatt are the ratio of the density of glass (of a mass of the same unit volume) with respect to water, which has a specific gravity (s.g.) of 1.000. Pellatt gives a recipe for the '[h]ighly pellucid and transparent Flint Glass,' noted as having a specific gravity of 3.200, as follows:

Carbonate of potash	1 cwt.
Red lead or Litharge	2 cwt.
Sand washed and burnt	3 cwt.
Saltpetre	14 lbs to 28 lbs.
Oxide of Manganese	4 to 12 oz.

It was sold to opticians in the form of annealed plates, flattened into pieces fourteen inches long, ten inches wide and, of about half an inch thick. Working a large pot of optical glass retarded glass-house operations. The quantity of usable glass was small and the unusable glass was no good for anything else.[63]

[63] A. Pellatt, *Curiosities of glassmaking*, London: D. Bogue, (1849), 41.

Chapter Three
Spectacles, telescopes and microscopes

It has been argued that since classical antiquity, craftsmen carving such small delicate items as seals and engraved gems could have used shaped pieces of rock crystal as magnifying lenses. Indeed, a plano-convex rock crystal lens in a modern-looking frame was excavated at Nineveh. The first European working of glass into hand lenses, or as spectacles, was in late thirteenth-century Florence. There is written evidence of spectacles being made there during the 1300s, and of Florentine shops selling them in the 1400s.[64] Venetian craftsmen soon followed; ordinances of 1300 and later have been interpreted as referring to spectacles to improve sight.[65] Illustrations from Italy and elsewhere show people wearing spectacles, and these offer more certain evidence than inventories, which can be misinterpreted, particularly in translation.

Figure 13: Hugo of Saint-Cher, fresco by Tommaso da Modena, 1352. Шуфель, Il Capitolo dei Domenicani, CC-PD-Mark.

Attention to the derivation of words is an aid to appreciating the complexity of interpreting inventories. The German word *brille* for eyeglasses derives from *beryllus*, or natural crystal. The English term *spectacle* could refer to the single eyeglass, a mirror, or even a window. Even the term `pair of spectacles' has been applied to a small form of medieval mirror consisting of a pair of mirrors, hinged in the form of a locket. Latin normally distinguishes between *speculum*, a mirror, and *spectaculum*, spectacles. A customs record of 1384 lists both *spectacul* and *specul,* indicating imports of both spectacles and mirrors. An

[64] G. Taddei, *L'arte del vetro in Firenze e nel suo dominio*, Florence: Felice le Monnier, (1954), 63–64.
[65] G. Albertotti, 'Lettera intorno alla invenzione degli occhiali all'onorevole senatore Isidoro Del Lungo.' *Annali di Ottalmologia e clinica oculistica*, 50, (1922), fasc.1–2, 5–24.

English-Latin word list of 1483 gives *speculum* as the Latin equivalent of a *merowe* (mirror), whilst a *spetakyl* is equated with the Latin *spectaculum*, *ocularis*, *oculare* and *spectacula*.[66]

The arrival of spectacles in England

A clear description of a pair of spectacles 'unum spectaculum cum duplici oculo, precii ijs' was listed among the effects of Bishop Walter de Stapledon of Exeter following his death in 1326.[67] These spectacles may have been imported, or more likely, acquired by the bishop during a visit to Rome. Reliable records of spectacles have been noted in many later English inventories. The range of values assigned to them lead us to the supposition, confirmed by contemporary illustrations, that some were in frames of precious metal, others in bone or leather frames, such as the pair of ox-bone frames excavated from a deposit in the City of London, dated to around 1440.[68] The use of a hollow tube to sharpen the view of stars, for example, was well known and was illustrated during the centuries prior to the arrival of the telescope.

The proliferation of printed books brought in its train a demand for spectacles and hand-lenses, and these in turn assisted elderly craftsmen to extend their working life. Flemish pedlars are thought to have been an important source of supply in England, presumably bringing over spectacles made in the Low Countries, although customs records also show imports from Rouen, another traditional source of spectacles.[69] It was early recognized that there were two principal defects of the human eye that could be rectified, or at least diminished, by either convex or concave lenses placed close to the eye. The most common defect was that of 'hypermetropia' or long sight, also known as 'presbyopia' or 'old sight', since it became more marked with age, and spectacles, comprising plano-convex lenses of varying curvature, were therefore marketed as suited to particular ages. Bi-convex lenses were apparently rare while concave or 'negative' lenses, suitable for those with myopia, are known to have been sold in Florence by 1451.[70] The fact that one order that year for three dozen lenses was filled within eleven days or less suggests that stocks of lenses, finished or at least part-finished, were held. There is

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[66] M. Rhodes, 'A pair of fifteenth- century spectacle frames from the City of London', *Antiquaries journal,* 62, (1982), 57–73; 64.
[67] F. C. Hingeston-Randolph (ed.), *The register of Walter de Stapledon, Bishop of Exeter (AD 1307–26)*, London: George Bell, (1892), 525.
[68] M. Rhodes, 'A pair of fifteenth- century spectacle frames from the City of London', *Antiquaries journal,* 62, (1982), 57–73; 57.
[69] According to C. Ouin-Lacroix, *Histoire des anciennes corporations d'arts et métiers,* Rouen, (1850), 262; the first guild of spectacle and mirror makers of Rouen was founded in 1538, but it seems that the trade had existed from earlier times.
[70] V. Ilardi, 'Eyeglasses and concave lenses in fifteenth-century Florence and Milan: New documents', *Renaissance quarterly*, 29, (1976), 345–360.

no documentary evidence for the manufacture of spectacles in London by the late sixteenth century. However, they could be procured there, as shown by a letter of 1598 written from Antwerp by the Derbyshire landowner and Roman Catholic conspirator Charles Paget to Thomas Barnes, Paget's instrument in London: 'Bring with you some eye glasses and spectacles, a dozen pair of 60 or 55 years' sight.'[71]

Beset by failing sight, the Duke of Saxony, August I of the House of Wettin, sent his secretary to buy him spectacles at Leipzig fair but there were none of good glass, so in 1574 the Duke sent him to Venice for crystal spectacles. August's secretary arrived in Venice during the summer drought. The glass-houses of Murano were closed down for fear of fire and those few spectacles available cost fifty thalers each, or twenty each for small glasses. This was a huge price, exceeding the cost of gold spectacle frames. August was always seeking good spectacles, and had the luck to obtain spectacle glasses from London at twelve thalers each. At his death, Duke August left thirty-six pairs of 'expensive' spectacles, those from Venice and London being the best.[72]

Extant treatises and remarks make it evident that lenses and mirrors were often used to focus the sun's rays to create a point heat source. Alchemists and astrologers also sought to focus and concentrate the light rays emanating from the moon, stars and planets. Images formed by these and other optical devices, in the shape of prisms, cylinders, pyramids, and polyhedra, were familiar subjects of experiment. In 1538 the Italian physician and astronomer Girolamo Fracastoro wrote in his *Homocentricorum sive de stellis liber unus* that by looking through two glasses (perspecilla ocularia), placed one over another, things are seen larger and closer. The Italian Jesuit philosopher and theologian Niccolò Cabeo, in his commentaries on Aristotle's *Meteorologia* of 1646,[73] mentions how the elderly men in their cells, poring over canonical literature, put one concave lens to the eye and held another over the page that they were reading.

Publication of William Bourne's treatise

The mathematician William Bourne wrote his *Treatise on the properties and qualities of glasses for optical purposes, according to the making and grinding of them*, in the form of a letter to William Cecil, Lord Burghley, shortly before Bourne died in 1582. The treatise was written as a response, as Bourne explained,

> for that of late your honour hathe had some conference and speeche with mee, as concerning the effects and qualitys of glasses, I have thought yt my

[71] Paget to Barnes, June 1598. **Cal. SPD** Addenda (1580–1624), 389.
[72] W. Münchow, 'Geschichte der Brille', *Der augenarzt*, 7, (1966), 479–540.
[73] N. Cabei, *In quatuor libros meteorologicorum Aristotelis commentaria, et quæstiones,* 3, Romæ, typis hæredum Francisci Corbelletti, (1646), 122.

> duty to furnish your desyer, according to such skill as God hathe given me, in these causes ... .[74]

Bourne does not identify his informants. He described the images cast by curved mirrors, which, as the viewer moved up to or away from the mirror, would swell or diminish, or go out of focus, or reverse. He then proceeds to deal with 'perspective glasses', which help sight by means of the beam that passes through them. The smallest sort, commonly called spectacle glasses, may be made of any kind of glass, but the clearer the better. Round pieces of thin glass are figured by being glued to a wooden block for ease of manipulation and then ground upon a concave iron tool, ending up thickest in the centre, that is, in modern terms, plano-convex. The thicker it is in the centre, writes Bourne, the larger the image. The result was an instrument that could assist in reading or doing fine close work.

Bourne proceeds to describe perspectives for 'any thinge, that ys of greate distance from yow, ...for to view an army of men, or any castle...'. These were specified as prepared from blanks of very clear white glass, such as Venice glass, and at least a foot in diameter. The glass would then require grinding on both faces, because of this the thicker the original sample the better. The finished lens must not exceed a quarter of an inch in thickness at the centre, with the edges very thin; a difficult task to accomplish. Looking through this glass, the image will increase in size as the viewer backs away. The implication is that distant objects would be clearly visible only if a large lens of the clearest glass could be prepared. Beyond the focal point, which Bourne defines as the burning point of the lens, the image is reversed. Bourne then considers the images that would be produced by a combination of concave mirror and convex lens. The expense of such devices is prohibitive to Bourne, but he knows that the mathematicians John Dee and Thomas Digges have had the leisure and learning to experiment with them. Lacking the experience of his own trials, he is led to believe that an incredible degree of magnification could be achieved, although, as he rightly observes, only a small region of the object viewed would be visible.

Publication of Giovanbattista's *magia naturalis*

The Neapolitan scholar Giovanbattista, or Giambattista, della Porta, also discussed the various images cast by mirrors, cylinders, pyramids and lenses of various configurations, used singly or in combination. His section on optical matters was first introduced into the second edition of his *Magia naturalis libri XX*, published at Naples in 1589 in Latin, an Italian edition following in 1611. An English edition, *Natural Magick in XX Books*, only emerged from a London press in 1658. Della

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[74] W. Bourne, 'A treatise on optical glass', (1582), **BL Lans**. 121. Published in J. O. Halliwell, *Rara mathematica*, London: John William Parker, (1839), 32–47.

Porta devoted a brief chapter to the manufacture of spectacles:

> In Germany there are made Glass-balls, whose diameter is a foot long, or there abouts. The Ball is marked with the Emril-stone round, and is so cut into many small circles, and they are brought to Venice. Here with a handle of Wood they are glewed on, by Colophonia[75] melted: And if you will make Convex Spectacles, you must have a hollow iron dish, that is a portion of a great Sphaere, as you will have your Spectacles more or less Convex, and the dish must be perfectly polished. But if we seek for Concave Spectacles; let there be an Iron-ball, like to those we shoot with Gun-powder from the great Brass Cannon: the superficies whereof is two, or three foot about: upon the Dish, or Ball, there is strewed white-sand, that comes from Vincentia [Vicenza], commonly called Saldane, and with water it is forcibly rubbed between our hands, and that so long until the superficies of that circle shall receive the Form of the Dish, namely, a Convex superficies, or else a Concave superficies upon the superficies of the Ball, that it may fit the superficies of it exactly. When that is done, heat the handle at a soft fire, and take off the Spectacle from it, and joyn the other side of it to the same handle with Colophonia, and work as you did before, that on both sides it may receive a Concave or Convex superficies: then rubbing it over again with the powder of Tripolis, that it may be exactly polished: when it is perfectly polished, you shall make it perspicious thus. They fasten a woollen-cloth upon wood: and upon this they sprinkle water of Depart, and powder of Tripolis: and by rubbing it diligently, you shall see it take a perfect Glass. Thus are your great Lenticulars, and Spectacles made at Venice.[76]

Following the publication of *Magia naturalis libri XX* della Porta continued to explore the possibilities of lenses and was aware of what the Italian scholar Galileo Galilei was attempting with his scholarly experiments to refine the performance of spectacle lenses, published in his *Dioptrice* in 1611. One section of della Porta's *De Refractione* published in Naples in 1593 (that is, after the Latin edition of the expanded *Magia Naturalis* but before its translations had appeared) dealt with the ray paths of light passing through variously figured lenses. He was engaged upon another treatise, *De Telescopio* when he died, but the manuscript itself was lost until, in 1940, it was discovered bound into the back of another tract. It reached the printed page only in 1962.[77] In this last work, della Porta—perhaps troubled

[75] Colophonia, or colophony, also called Greek pitch, was a resin distilled from turpentine.
[76] J.B. della Porta, 'The seventeenth book,' in *Natural magick*, London: Thomas Young and Samuel Speed, (1658), 355–381, on 379.
[77] A. M. Naldoni, 'L'ottica del Porta dal "De reflectione" al "De telescopio"', *Storia della scienza*, (1962); Book Five of *De telescopio* (the earlier parts were intended to deal with refraction and lenses, only the fifth book was on the telescope itself), reproduced with Italian translation in V. Ronchi, *Scritti di ottica,* Milan: Il Polifilo, (1968), 244–263.

by excessive chromatism—pursued the false theory that by substituting lenses with one plane face the rays would be less 'broken' or dispersed and a vastly more powerful telescope could be made.

Arthur Hopton, astrologer and mathematician, gave a similar account of distant vision being achieved with a combination of lens and mirror in his *Speculum Topographicum or the Topographical Glasse*, published in 1611:

> We have an imitation of such glasses as these about London commonly to bee sold, but they be so small that they stand one in small steede, but amongst the writers of perspective, I have read that if you take a glasse of the same metall that burning glasses be, and 16 or 17 inches broad, whose centre place directly against ye object you looke upon, and let it not incline, or hang sideways by any means, behind this glasse set a faire looking glasse, the polished side beholding the said burning glasse, to ye intent to receive the beames that come through the same: which done, look in the looking glasse, so shall you have your device, if the burning glasse were truly placed: for you must note whatever thing you see through the burning glasse, that the further you stand from the glasse, the bigger it seemeth, untill you come to a certain distance, and then the object seen through the glasse doth seeme lesser and lesser, therefore care must be had in placing the glasses, so may you view a town or castle, or any window in the same, 6 or 7 miles, or see a man 4 or 5 miles, read a letter in written hand a quarter of a mile from you &c.[78]

In 1638 Marin Mersenne (see Chapter Six), an apostolate of the intellect in the Minim Convent de I'Annonciade, approved a book for publication by a fellow Minim in the same convent, Jean-François Niceron. The book was *La perspective curieuse* and its principal concern was to explain to artists, architects, sculptors and engravers the perspective of images cast by variously figured smooth and polygonal lenses and mirrors. Niceron allows that such images may be so strange in their distortions, so magnified or diminished, even changed in colour when certain chemicals are added to the glass, that they seem like products of sorcery or supernatural forces; but he can demonstrate mathematically that this is not so.

La perspective curieuse also gives a clear explanation of the manufacture of plane, spherical and cylindrical mirrors. Plane mirrors should be of best crystal foiled with tin and mercury, but mirrors with curved surfaces cannot be accurately shaped from glass and must be of 'mirror steel', which is an alloy of several metals. He gives several recipes differing in their proportions but broadly composed of

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[78] A. Hopton, 'Chapter 100. To make a glasse whereby to discerne any small thing, as to read a written letter a quarter or half a mile off,' in his *Speculum topographicum, or the topographicall glasse*, London, (1611).

copper, tin, some makers adding small quantities of one or more of the following: marcasite of silver (probably iron or copper pyrites having a silver lustre), arsenic, saltpetre, tartar, and grease. The molten metal was poured into a shaped sand or cast by the *cire perdue* process—that is, lost-wax casting. Niceron suggests a wide variety of polishing materials, which included all those used on glass lenses.

From lens to spy-glass

Historians have debated why so many years elapsed between the invention of spectacles and the invention of the telescope. One theory is that, because lenses altered the size or overturned the image of things seen through them, it was believed that they in some way perverted truth, and while old people might benefit from them, they were shunned by men of science. Some hint of this idea does emerge from various early textbooks. In his *Magia universalis naturae et artis*, 1657, Gaspar Schott, a Jesuit who studied and taught in Palermo and later at Würzburg, sought to lead the reader from the magical optics of illusions and false images to the practical, useful and truthful optics.[79] By the latter, Schott had in mind the prescription and making of spectacles, as well as telescopes, microscopes and other apparatus. The possibility exists that the makers or wearers of spectacles mounted in frames hinged to grip the nose might from time to time have folded the frame so as to read through both lenses.

Experiments with lenses and mirrors were practiced long before the arrival of the telescope; though 'spy-glass' is more appropriate for these early forms understanding that device as comprising two or more lenses fixed within a tube, whose distance could be varied by sliding one portion of the tube within the other. Van Helden has proposed that the construction of the spy-glass was inevitable, and that it was in fact invented before anyone, including the craftsmen who made them, was aware of it. Van Helden's argument follows that della Porta and others had shown what could be achieved with a combination of lenses, but the optical benefit of constructing a permanent form of this arrangement—namely, fixing the lenses within a tube—had not previously occurred to anyone. Van Helden assigns this achievement to the spectacle-maker Hans Lippershey [Lipperhey] of Middleburg in the Low Countries, in 1608.[80]

The origins of the telescope were much discussed in the years following its dispersal within the scientific community, and as might be expected, several persons came forward claiming to have been the inventor. On 2 October 1608 Lippershey applied to the States-General for a patent for a term of thirty years, or

[79] G. Schott, *Magia universalis naturae et artis,* Würzburg, (4 vols., 1657–1659). See also *ibid.*
[80] A. Van Helden, `The invention of the telescope', *Transactions of the American Philosophical Society*, 67 (1977), 1–67.

for an annual allowance to supply this instrument on behalf of his country alone, not to foreign princes and others. A committee was set up to negotiate with him, and their deliberations reveal details about the lenses fitted in these early spy-glasses. The instrument was to be tested from the tower of Prince Maurice of Orange's quarters, and if found satisfactory, the committee would order instruments of rock crystal to be completed within one year, but at a price lower than the thousand guilders each which Lippershey had set upon them. On 6 October 1608 the committee ordered one instrument, at a cost of three hundred guilders deposit and six hundred on completion, whereupon they would decide whether to award the patent or annual allowance, provided Lippershey made no such instruments without consent. But on 17 October 1608 the Dutch geometer and astronomer Adrian Metius petitioned for a twenty-year patent, claiming to have invented a spy-glass as good as that of Lippershey, but that his instrument was 'of bad material.' He was awarded one hundred guilders and told to improve his invention. By this time officials of the States-General became aware that there was a number of these spy-glasses in circulation and that their manufacture could hardly be kept a secret. On 15 December the committee tested Lippershey's binocular spy-glass. The patent was refused, however, on the grounds that other craftsmen already knew how to make these glasses.[81]

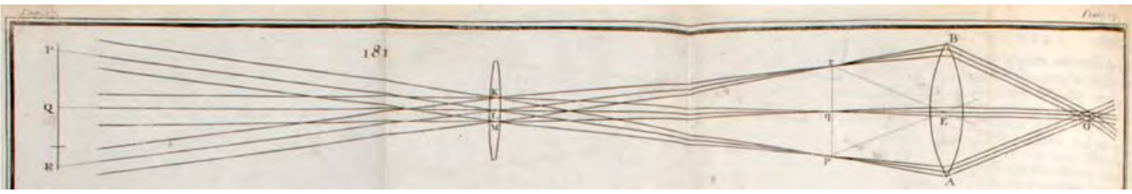

Figure 14: The passage of light through a refracting telescope for astronomical use. 'PQ' represents the semidiameter of a remote object, 'pq' is the picture formed by the convex lens of the object-glass, labelled 'L'. 'EA' represents another glass more convex than 'L'. The object appears to the eye at O, distinct, inverted and magnified. Smith goes on to explain how much the image is magnified and why. Robert Smith, *A Compleat system of optics in four books: A popular, a mathematical, a mechanical and a philosophical treatise,* Cambridge, 1738, Book 1, 37, plate 14, fig. 181. © Whipple Library, Cambridge, STORE 66:12.

These Dutch two-lens spy-glasses magnified three or four times and, as the States-General had feared, their military value was immediately recognized in those times of strife. Sovereigns encouraged their improvement to ensure, if not their exclusive use, at least the advantage of quality. Public interest led to their rapid diffusion in major European cities. Astronomers and scholars with an interest in optics saw them as opening the way to discovery, to the greater glory of science and the honour that would accrue to themselves and their patrons.

[81] G. Doorman, *Patents for inventions in the Netherlands during the 16th, 17th and 18th centuries*, The Hague: Nijhoff, (1942), 71.

News of this useful instrument travelled fast and actual examples, presented as gifts or carried by merchants, were close behind. A spy-glass was offered for sale at the Frankfurt fair in the autumn of 1608.[82] The invention was noticed in diplomatic and official gazettes with a wide dispersal, including England. A notice was circulated at The Hague 'concerning certain 'lunettes' which had been presented to Count Maurice, by which one could distinctly perceive objects three or four leagues distant as if they were 100 paces away.' A manuscript copy of this notice and, several days later, four printed copies, reached the Parisian diarist and collector Pierre de L'Estoile. On 23 November 1608 de L'Estoile noted that he had given one to the English ambassador in Paris, another to Courtin, and a third to de Lassi.[83] Galileo also came to hear of it.

Le mercure François was an annual compilation of court and crown news published in Paris and founded in 1605. The issue of 1611 related that in April 1609 spy-glasses were available from spectacle-makers in Paris.[84] In May a Frenchman came to Milan to offer the device to Pedro Henriquez d'Azevedo y Alvarez de Toledo, Count of Fuentes, saying that he was an associate of the inventor in Holland.[85] Girolamo Sirtori, author of *Telescopium*, the earliest book on the telescope, said that the Count passed it to a silversmith to have it put into a silver tube. Putting these spy-glasses into the hands of craftsmen in other cities must have helped to spread knowledge of their construction. A Dutch spy-glass was taken by a Frenchman—possibly the same man—to Padua at the end of July 1609. Galileo was in Venice at the time, but heard of it. He returned to Padua on 3 August but the Frenchman had by then moved on to Venice. Giovanni Bartoli, the secretary of the Medici representative in Florence, Belisario Vinta, wrote his employer on 26 September 1609, that a Frenchman, presumably the same man, was secretly making telescopes in Venice and that the most perfect had lenses of mountain crystal and were very expensive, ten or twelve scudi just for the glass, while those of Murano crystal or ordinary glass cost three or four zechini, or as little as two zechini.[86] Around 1616 spy-glasses were also sent from Venice to India, where they were immediately replicated by local craftsmen, to the regret of the European traders who thus won and lost a market.

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[82] S. Marius (Mayr), *Mundus jovialis,* Nuremberg, (1614), preface, reproduced with English translation in A. Van Helden, 'The invention of the telescope', *Transactions of the American Philosophical Society*, 67, (1977), 46–47.
[83] P. de l'Estoile, *Memoires—journeaux*, 9, (1881), 164, 168.
[84] *Le mercure Francois*, reproduced with English translation in A. Van Helden, `The invention of the telescope', *Transactions of the American Philosophical Society*, 67 (1977), 47–48.
[85] G. Sirtori, *Telescopium, sive ars perficiendi*, Frankfurt, (1618), 23–30; reproduced with English translation in Van Helden, *ibid.*, 50.
[86] G. Taddei, *L'arte del vetro in Firenze e nel suo dominio*, Florence: Felice le Monnier, (1954), 68, citing Galileo, *Opere* 10, 259.

The astronomer's telescope

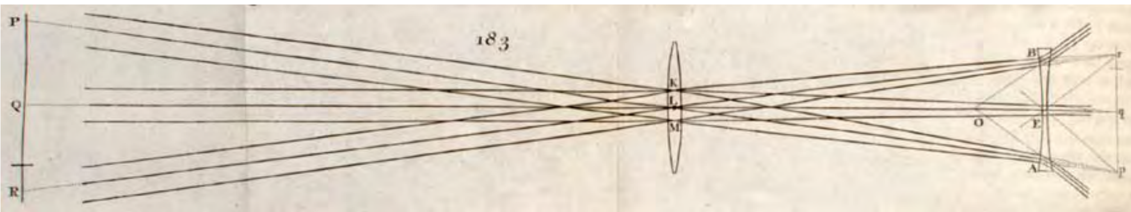

Figure 15: The passage of light through a Galilean telescope, which differs from the astronomical telescopes described in figure 14 and figure 17 in combining a convex and concave lens. The convex object-lens converges rays of light that are diverged by the concave eyepiece lens. The result was a non-inverted, magnified and distinct image. Robert Smith, *A Compleat system of optics in four books: A popular, a mathematical, a mechanical and a philosophical treatise,* Cambridge, 1738, Book 1, 37, plate 14, fig. 183. © Whipple Library, Cambridge, STORE 66:12.

The day after Galileo's return to Padua he wrote to his close friend in Venice and fellow experimenter into lenses, the natural philosopher and theologian Paolo Sarpi that he had discovered the secret of the spy-glass. On 21 August he took a finished telescope to Venice. Galileo had no knowledge of glass-working and lens grinding was a specialist craft; though Sarpi, with his Venetian glass contacts, may have assisted. However, the Dutch glass was so simple in its arrangement that many competent persons might have guessed at its construction, nor is it entirely certain that Galileo had not seen or had described to him just such an instrument. Galileo's first telescope, already an improvement on the Dutch spy-glasses, magnified eight times. By November 1609 he had a telescope that magnified twenty times, and he turned it to the sky with satisfying results. By early 1610 one hundred instruments—it is uncertain whether these were lenses or telescopes—had left his hands. In his attempt to improve the performance of his telescopes, and to meet the demand from his wealthy patrons and clients, as well as those of his friends, Galileo employed a number of craftsmen, recruited from Venice, Murano, Padua and Florence, to grind his lenses. These were men trained in the craft of spectacle-making, or of grinding and polishing mirrors and *pietre dure*: the hard stones used in decorative inlays and other artifacts.[87]

The Jesuits of the Collegio Romano recognized in 1611 the need to revise the Ptolemaic system of the world on the basis of Galileo's telescopic discoveries. From this point on, the success of the telescope was such that neither the ecclesiastical censure of the Copernican theory in 1616, nor the condemnation of Galileo for heresy in 1633 could stop the spread of the instrument. In Florence telescopes were made by Ippolito Francini, under the name Il Tordo, Jacopo Mariani, known as Il Tordino, and the young mathematician Evangelista Torricelli. Their

[87] S. A. Bedini, 'The makers of Galileo's scientific instruments', *Atti del simposio su Galileo Galilei nella storia e nella filosofia della scienza, Florenza-Pisa 1964*, (1967), 89–115.

instruments competed with Galileo's, both in terms of lens-making and in magnifying power.

The first spy-glasses comprised a concave and a convex lens secured in a tube or tubes made from pasteboard; metal most likely tin or iron; or *arundino*, probably cane. Della Porta described the one he had seen in August 1609 as being 'three fingers' in diameter, '[sliding] in and out like a trombone', in two tubes, one four fingers long, the other a palm's length (just over ten inches).[88] Della Porta was unimpressed by what he considered to be a hoax, something copied from his own book on refraction.[89] His words and the accompanying sketch nevertheless remain the first depiction of a telescope that can be adjusted to suit the eyesight of different observers.

In fact, although common spectacle lenses were adequate to demonstrate the principle, the construction of a spy-glass called for convex lenses having a greater radius of curvature. The nobleman Johann Philipp Fuchs von Bimbach had seen the telescope offered for sale at Frankfurt but had declined to pay the price asked for it. On returning home he conferred with the astronomer and mathematician Simon Mayr. They experimented with spectacle lenses, and realised that they needed a convex lens of greater radius of curvature. They modelled this shape in plaster and sent it to Nuremberg but none of the lens grinders in that city, famous for its optical workshops, had tools that would enable them to replicate it.

The astronomer Johannes Kepler had written to Galileo on 9 August 1610,

> You have aroused in me a passionate desire to see your instruments [...] of the oculars which we have here the best has a tenfold enlargement, the others hardly a threefold. The only one which I have gives a twentyfold enlargement but the light is very weak. The reason for this is not unknown to me and I see how the intensity could be improved, but one hesitates to spend the money.

Kepler published his experiments with the various combinations of lenses in his *Dioptrice seu demonstratio eorum quae visui et visibilibus propter conspicilla non ita priden inventa accidunt* at Augsburg in 1611. He proposed what became known as the Keplerian telescope, which replaced Galileo's concave eyepiece by a convex one, and this was made up by the Jesuit Christoph Scheiner in around 1615.[90] Multi-lens telescopes came into general use around the mid century; they afforded

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[88] Della Porta to Federigo Cesi, 28 August 1609. Galileo, *Opere* 10, 252.

[89] His complaint referred to Book 9 of his *De refractione*, which dealt with colours of the rainbow.

[90] J. Kepler, *Dioptrice seu demonstratio eorum quae visui et visibilius propter conspicilla non ita pridem inventa accident*, Augsburg, (1611).

a wider field of view, less spherical aberration and fewer coloured fringes.[91]

Galileo's problem was to find a good quality glass. He too, like the elusive Frenchman said to be operating in Venice, tried German glass, rock crystal and also pieces of mirror glass.[92] Taddei claims that the reason for Galileo's disregard of the Murano glass-works as a source of fine crystal glass was not, as has been suggested, that it was in short supply, but that after his transfer to Florence in September 1610 he was able to supervise glass-making experiments there, paid for by his patron Cosimo II de' Medici, Grand Duke of Tuscany.[93] There had been glass-works in the surroundings of Florence for centuries, supplying the spectacle-makers of that city. By the time that Galileo arrived, crystal was being produced, made from 'tarso', a hard quartz from the Pisani mountains and elsewhere in the vicinity, ashes of 'rochetta di Levante' or Syrian saltwort, and manganese, the best coming from Piedmont.

Figure: 16 Portrait of Evangelista Torricelli, from the frontispiece to *Lezioni accademiche d'Evangelista Torricelli*, 1715. Quibik, Treasures of the NOAA Library Collection, Image ID: libr0367, CC-PD-Mark.

The performance of telescope lenses was greatly advanced by Evangelista Torricelli. The young mathematician joined the blind and aged Galileo in October 1641 together with Vincenzo Viviani as companion and assistant. Their collaboration was short-lived for Galileo died in January 1642 and Torricelli found himself promoted to succeed Galileo as mathematician to the Grand Duke. In the five years that remained of his own short life, Torricelli developed an interest in lens grinding that led him to become the outstanding practitioner of this art. Baltasar de Monconys of Lyon bought several telescopes and microscopes from Torricelli in 1646, one of which was delivered to him at Cairo one year later.[94] Modern examination of Torricelli's lenses shows them to be more perfect than any being made at that time. From letters to his friends, we know that he ground and polished the lenses on glass,

[91] Mersenne to Peiresc, [?September] 1635, **Mersenne**, 5, (1959), note to Letter 476.

[92] A list in Galileo's hand on the outer cover of a letter sent to him on 23 November 1609 includes `vetri todeschi spaniati; spianar cristallo di monte; pezzi di specchio; feltro, specchio per fregare', besides other domestic requirements. Lettera 255, Galileo, *Opere* 10, 270.

[93] G. Taddei, *L'arte del vetro in Firenze e nel suo dominio*, Florence: Felice le Monnier, (1954), 68.

[94] B. de Monconys, *Voyage de M. Monconys*, vol. 1, Lyon, (1665–6), 114–5, 117, 130–1, 273.

rather than metal, forms. He did however have a 'secret', which the Grand Duke ordered him to keep to himself, and although a long letter to Italian mathematician Bonaventura Cavalieri in 1642 explained his procedure step by step, the 'secret' was not disclosed 'for the sake of brevity'.[95]

When Torricelli was dying, the secret was written down and placed in a locked box that was handed to the Duke. Following Torricelli's death this box was given to Viviani who inherited the post of mathematician but had no interest in lenses. The box and its contents were presumably destroyed or lost, for they have never been heard of since that time. Recently a lens signed by Torricelli has been found at Naples and subjected to various chemical and physical tests. From its dimensions, it is probably one of those about which he wrote to the Jesuit Raffaelo Prodanelli on 14 October 1645. At 11.1 cm in diameter, with a focal length of 596 cm (about thirty-two palms), with a specific gravity of 2.493, the glass is in no way unusual.[96] It has been suggested by modern opticians that Torricelli's secret of success lay not in his grinding or polishing procedures, but in his appreciation of the wave-quality of light, and that he used the interference patterns on the lens to guide his hand in the final polishing.[97]

The basic assemblage of a dispersing, convex, objective lens and a converging, concave ocular soon yielded to elaboration, with three, four, or even six, lenses being ranged within draw-tubes. Given the poor quality of even the best glass, this must have severely reduced the amount of light reaching the eye. Galileo made the valuable discovery that inserting a brass diaphragm to mask the rim of the lens and reduce the aperture sharpened the image.[98] Further it was found that extending the tube beyond the objective, to shield it from direct light, also sharpened the image. The purpose of such combinations of lenses was in some cases to generate an erect image, where the image is in the same orientation as the object, and in other cases to increase the field of view.

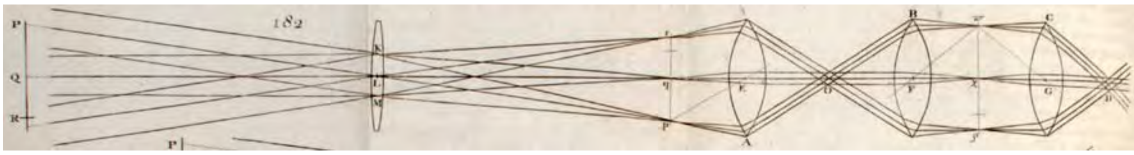

Figure 17: The passage of light through a refracting telescope made of four convex glasses. Smith describes how object that appeared magnified and distinct but inverted in Figure 14 will appear upright through two more convex eye-glasses subjoined to it. Robert Smith, *A Compleat system of optics in four books,* Cambridge, 1738, Book 1, 37, plate 14, fig. 182. © Whipple Library, Cambridge, STORE 66:12.

95 Torricelli to Cavalieri, 25 October 1642. Torricelli, *Opere* 3, 79.
96 G. Paternoster *et al*, `Studio di una lente per cannocchiale di grandi dimensioni lavorata da Evangelista Torricelli', *Nuncius*, 11(1), (1996), 123–134.
97 V. Ronchi, *Scritti di ottica,* Milan: Il Polifilo, (1968), 441–451.
98 Galileo, *Opere* 10, 278.

The telescope's utility was instantly apparent to military and naval men as well as to astronomers. For military use, an erect image was essential, and the distances over which the telescope would be useful were probably limited. Astronomers, whose telescopes were at first turned on the moon and the larger planets were effectively focusing at infinity and were able to accept an inverted image. Prudent men learnt to avoid direct observation of the sun and observed sunspots by focusing the projected image onto a flat white surface. In an effort to reduce chromatism, the focal length of telescopes was increased until they became unwieldy and the tube holding the lenses flexed under its own weight. A solution was sought by constructing the short-lived 'aerial' telescopes, in which the lenses were held in a frame rather than a tube. This arrangement allowed the objective to be placed up to several hundred feet from the ocular, but must have been extremely difficult to hold steady. Others have explored the history of the telescope, but whatever its construction, the telescope's performance depended above all on the quality of its lenses.

The microscope

The concern of lens quality, crucial to the telescope's performance, was also central to the operation of the microscope and is made explicit in the correspondence of microscopists such as Cornelis Drebbel, amongst others. The telescope revealed sights that conflicted with received belief concerning the created universe. The supposedly pure sun displayed a blemished face, while Jupiter's encircling satellites were hard to explain within the concept of an earth-centred cosmos, a concept already being questioned. The Jesuit professor Gaspar Schott, in his four-volume *Magia Universalis naturae et Artis*, published at Würzburg in 1657, sought in the first volume to bridge the mental gap between the magic of illusion and the images produced by lenses, mirrors and other devices, which conformed to the laws of optics. The invention of the microscope, following closely on that of the telescope, brought into view the miniscule life in a drop of water, and displayed the previously invisible structure of a strand of a feather or slice of cork. The origin of the microscope is even less clear-cut than the telescope, not least because it was possible to use the same device for both distance and close magnification. Thus John Wedderburn (or Wodderburn), a Scottish mathematician in Galileo's circle, noted in a book published as early as 1610 that Galileo had recounted to the Italian professor of natural philosophy Cesare Cremonini,

> [how he had] perfectly distinguished with his telescope the organs of motion and of the senses in the smaller animals, and especially in a certain insect which had each eye covered by a rather thick membrane which is perforated by seven holes like the visor of a warrior to allow it sight.[99]

[99] J. Wodderburn, *Quatuor problematum ...*, Padua, (1610), 7.

While a Galilean telescope with a convex objective and a concave eyepiece will show minute details of insects, it has a very small field of view. The French canon Jean Tarde, who visited Galileo in 1614, recorded that while the stars could be observed through a telescope two feet in length, a tube four to five feet long was needed to see tiny organisms. Four to five feet seems an inconvenient size for a microscope, although Galileo informed Tarde that through such a tube he had seen flies which appeared as big as lambs.[100] It seems that Galileo took no further interest in this instrument until news of Drebbel's microscope reached him, around 1622. He was unable to replicate it, however, until examples arrived in 1624. After this Galileo manufactured several microscopes which he gave to friends in 1624. It is thought these were like those of Drebbel, Keplerian instruments with two convex lenses.

Figure 18: Portrait of Cornelis Drebbel, woodcut by Christoffel van Sichem, 1631. EFFemeer, http://www.archiefalkmaar.nl/, CC-PD-Mark.

Cornelis Drebbel, Dutch by descent, lived both in Holland and in England, where his daughter also resided. Scorned by some as a charlatan for his perpetual motion machine, others have hailed him as the inventor of the submarine, the barometer and the microscope. Something of a showman with the gift of disguising that which he saw as a valuable trade secret, he seems also to have been skilled at handling glass and he was well-received by James I of the House of Stuart, who installed him in a workshop close to the Minories in London, in the hopes that his submarine and other warlike devices would be of military value.

Drebbel was in Middelburg around 1600, erecting a fountain there that year. He was familiar with the glass grinders and with the important glass-works supplying them, and he was skilled at making various optical devices such as his mirror that multiplied the image of the object or person facing it. In 1620 he was, according to amateur astronomer and mathematician Nicolas-Claude Fabri, experimenting to prepare glass which would be a substitute for rock crystal, as those who had made a telescope for Henry, Prince of Wales had been unable to make such glass and had been obliged to employ rock crystal. Nicolas-Claude Fabri took the landed title de Peiresc in 1624, he shall be referred to as Peiresc from here in. It is unclear whether Drebbel’s experiments into glass substitutes for rock crystal were undertaken when he was in Middelburg or in London. Drebbel told Peiresc that he

[100] *Relazione dei viaggi*, published in F. Moureau and M. Tetel, (eds.), *Jean Tarde à la rencontre de Galilée. Deux voyages en Italie,* Geneva: Slatkine, (1984).

had been charged with obtaining from Italy a piece a foot and a half long and as thick as his arm, to be melted down.[101] Two years later Constantyn Huygens, the erudite secretary to Frederick Henry, Prince of Orange, reported how, in a conversation with Drebbel, the latter had dismissed the idea that the best telescopes were made in England, maintaining that it was the quality of glass, or rock crystal, that mattered, and that given an understanding of optics, all countries would be on an equal footing.[102]

It is probable that Drebbel taught Constantyn Huygens how to grind glass in 1622, and Constantyn passed this knowledge to his son Christiaan. Drebbel's two daughters Anna and Catharina, married brothers, Abraham Kuffler and Johann Sibertus, who were involved with Drebbel and later established a dyeworks. Robert Hooke, who was also acquainted with Drebbel's daughter and son-in-law, may likewise have learnt glass grinding from Kuffler. Drebbel is the first of whom it is recorded that he had a glass grinding machine at his house near London. Peiresc wrote that on this machine Drebbel could make lenses to any required measurement and each one the same, and that it was very easy because he had merely to set the machine up and leave a small boy to operate it, just looking in every three or four hours.[103] There is no doubt that Drebbel made numerous telescopes, and that Constantyn Huygens was a customer, purchasing them for himself and his friends.

Whether or not Drebbel constructed the first composite microscope with two convex lenses, he certainly made such microscopes known over western and southern Europe. Drebbel showed Willem Boreel, Dutch ambassador in London in 1619, a microscope he claimed had been made for the Archduke Albert VII of the House of Habsburg, by the spectacle-maker Sacharias Janssen, also spelt Zacharias Jansen, of Alkmaar. The tube of this instrument was about a foot and a half long and just over an inch in diameter, and would seem to have been a version of the Dutch telescope. The two Huygens, father and son, believed that Drebbel had been making such microscopes from at least 1621, when one was shown in London, and Constantyn marvelled at the objective lens, no thicker than the nail of his little finger.[104] Drebbel's microscopes were already in the hands of James I, Prince Maurice of Orange, and the Gaston I of the House of Bourbon, Duke of Anjou when he sent Jacob Kuffler, younger brother of his sons-in-law, to Europe with the intention of making further sales.

[101] Peiresc 1776, [Life of Drebbel]. **Bibl. Inguimbertine.** f.411v.
[102] Constantyn Huygens to his parents, 3 January 1622. In J. A. Worp (ed.), *Constantyn Huygens briefwissling,* vol. 1, (1911–17), 76–77.
[103] Peiresc, 1774, **Bibl. Inguimbertine**. f.408.
[104] Constantyn Huygens, *Autobiography*, `Fragment eenen autobiographie van Constantyn Huygens', *Mededeeling van het historisch genootschap,* 18, The Hague, (1897), 100–103.

Peiresc, who had been present when Kuffler demonstrated one of Drebbel's early microscopes in Paris on 22 May 1622, carefully examined the size and figure of the lenses. It consisted of three tubes, able to slide one within another, 'about the thickness of a wrist'. The eyepiece aperture was 'the size of a small nail' and the eye lens was a small sphere set about two fingers' distance from the aperture. At the far end was a plano-convex lens, the flat side turned towards the eyepiece, the convex side masked by a brass diaphragm. Kuffler argued that this lens was neither a regular convex nor concave. Further he claimed that it was not merely ordinary glass, because as it was congealing Drebbel threw a certain substance on it to improve the clarity.

Peiresc described the objective of the microscope as 'half a small bulb, about the size of a small cherry'. Objects viewed through this were seen reversed, so that an insect walking to the left was seen walking to the right.[105] Peiresc acquired at least two of these microscopes from Kuffler, and he assisted Kuffler with letters of introduction to various influential persons in France and Italy. Kuffler died of the plague in Rome in November 1622 without having displayed his new instruments, and as a result the two examples that Peiresc sent to Rome in August 1624 were the first to be seen there. Although accompanied by instructions, the Italians were unable to make them work, which suggests that Peiresc had sent only lenses, leaving the tubes and other fittings to be made locally. As had been the case for Galileo, the craftsmen were unable to replicate Drebbel's arrangement until they examined the instrument itself. In 1625 Abraham and the another of the four brothers, Gilles Kuffler, were travelling Drebbel's microscopes in Germany, and demonstrated one to the papal doctor, botanist and art collector, Johannes Faber (or Fabri), who bestowed upon it the name of 'microscope' by analogy with 'telescope'.[106]

The Jesuit Felipe Buonanni (or Bonanni), in his *Musaeum kircherianum,* (1709), prefaced the section on Kircher's microscope drawings with a brief rehearsal of books dealing with optical instruments and a list of makers, living and recently deceased, taken from these books, plus the *Travels of Baltasar de Monconys*, and presumably, his own knowledge. Anglicised from the Latin where possible, they are Felice Fontana, Emanuel Maignan, Johannes Hevelius, Johann Wiesel, Gervase Mattmüller, Evangelista Toricelli, Manfredo Settala, Guillaume Ferrier, Daniel Chorez, Guillaume Ménard, Stephan Bressieux of Grenoble, Chalamonius 'Aquensis'[107], de Servie of Leiden, Cornelis Drebbel, Isaac Vossius, de Hudd, Theodore Moretus SJ of Bratislava, Basil Titel, Christopher Weieman (possibly Weinmann), Giuseppe Campani, Adrian Enricus de Ravesway, Carolus Antonius

[105] Peiresc, 1774, **Bibl. Inguimbertine.** f.407r,v.
[106] Johannes Faber, in Fr. Hernandez, *Nova plantarum, animalium, et mineralium Mexicanorum historia*, Rome, (1648–51), 473.
[107] Three different towns bore the name Aquensis.

Tortoni, Marcus Antonius Cellius, John Baptist Vanini of Florence, Johann Franz Griendel von Ach. Some of these names have already been mentioned; others are probably those of now obscure amateurs or tradesmen.

Professional optical instrument makers

While the lenses produced by Galileo and Torricelli after him were sought after outside Italy, craftsmen in other countries were also learning to manufacture them. Galileo tried to interest the Spanish crown in the military advantages of his telescopes, and a glimpse of the technology of lenses in that region around 1620 is disclosed in a book by Benito Daza de Valdés, who was an official in the Office of the Inquisition at Seville. Entitled *Uso de los antojos para todo genero de vistas...* and published at Seville in 1623, it deals above all with the human eye, its characteristics, changes with age, and individual defects, and how these may be relieved by the use of the appropriate lenses. A series of dialogues are presented where the doctor, the patient, a spectacle-maker and a commentator discuss each case. The best lenses, according to Valdés, are made of rock crystal, the next best are of mirror crystal from Murano, where they make spectacles as good as those of rock crystal, the advantage being that mirror crystal is less hard and therefore easier to work; lenses of common glass are virtually useless.

The final dialogue concerns telescopes. The characters visit the craftsman's house where he has a variety of telescopes, ranging from a few inches in length to one that extends to over twelve feet. The visitors are invited to test these remarkable telescopes for themselves, and they marvel at this new invention. Nothing is said about the source of the invention. Galileo had attempted over many years to interest the Spanish Admiralty in his method of finding longitude by observations of Jupiter's satellites, only to be spurned because it was thought impractical to employ the telescope at sea. Nonetheless perhaps with his relation to the Inquisition, Valdés suppressed Galileo's name. In the light of the few surviving copies, this book appears to have had a limited circulation. It was, however, translated into French in 1627, the manuscript surviving in the Bibliothèque Nationale.[108]

Johann Wiesel was among the first craftsmen to establish a workshop specifically for the manufacture of telescopes and microscopes.[109] Wiesel originated in the

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[108] **BN** Fonds Français 14735. A note on the obverse of one page indicates three other works, two on eyeglasses, the third is `Syrturi telescopium'.

[109] This section draws largely on the published and unpublished work of Inge Keil (d.2010), principally her *Augustanus opticus: Johann Wiesel (1583–1662) und 200 jahre optisches handwerk in Augsburg* (2000); `Technology transfer and scientific specialisation: Johann Wiesel, optician of Augsburg, and the Hartlib circle' in M. Greengrass, M. P. Leslie and T.

Rhineland Palatinate, and later moved to the imperial city of Augsburg. Through his marriage in 1621 to the daughter of a citizen and craftsman of Augsburg, he himself acquired citizenship, with the right to practice his craft there. Optical instrument making was a 'free art', and so he was not required to become a member of one of the craft corporations. Unlike Nuremberg and Regensburg, there was no incorporated craft of spectacle makers in Augsburg. The first letters to mention Wiesel's optical apparatus—eyeglasses, perspectives, flea glasses, burning mirrors, and camera obscuras—date from 1625. Instruments were prepared for several German dukes and subsequently for the German emperor Ferdinand II of the House of Habsburg. They were supplied to King of Sweden, Gustav Adolphus of the House of Vasa, following his conquest of Augsburg in 1632, and to Giovanni Battista Riccioli of Bologna, being used by him for his map of the moon.[110] Wiesel continued to produce optical instruments even during the difficult period of the Thirty Years War, and in 1638 he was joined by Daniel Depier (variants include Depiere and de Pier), a glass-worker from Danzig, who two years later married Wiesel's daughter, and continued his business in after years.

Figure 19: Map of the Moon from Giovanni Battista Riccioli, *Almagestum novum,* 1651. Wiccioli, Almagestum Novum, CC-PD-Mark.

Raylor (eds.), *Samuel Hartlib and universal reformation*, Cambridge: Cambridge University Press, (1994), 268–278; `Der Augsburger optiker Johann Wiesel und seine beziehungen zu Herzog August dem Jüngeren von Braunschweig-Lüneburg', in J. Brüning and F. Niewohner (eds.), *Augsburg in der frühen neuzeit,* Colloquia Augustana 1. Berlin, (1995), 158–169.

[110] G. B. Riccioli, *Almagestum novum,* Bologna, (1651), I, 204.

Wiesel's products were already known in Europe when a book written by a Capuchin monk, Anton Maria Schyrleus de Rheita ('de Rheita' refers to his birthplace, Reutte, in the Tyrol) entitled *Oculus Enoch et Eliae*, was published at Antwerp in 1645. Rheita claimed to have taught Wiesel much suggesting that he supplied the necessary mathematical knowledge. He described telescope manufacture and, in a cryptogram, mentioned a hitherto-unknown compound eyepiece for telescopes, comprising three collective lenses, which would show objects upright. These telescopes could be obtained from Wiesel and from Gervase Mattmüller in Vienna. In succeeding years Wiesel sold telescopes of this pattern, with four or more convex lenses, all over Europe. He also sold compound microscopes with three convex lenses. He was probably the first optician in Europe to embody the field lens in his microscopes in 1650, to give a greater field of vision.

Chapter Four
European networks and the first telescopes in England

Figure 20: Seven-draw refracting telescope, [unknown maker], English, circa 1700, © Whipple Museum, Cambridge, Wh.1828.

Telescopes in France

Numerous lenses and telescopes were either imported into France or prepared within the country prior to the foundation of the Paris Observatory in 1672, but the identity of their makers is generally unknown. One of the first professional opticians in France was Daniel Chorez of Paris, who was also an engraver and mathematical instrument maker. Chorez presented the French king with a telescope in 1620, and he is known to have made at least two binocular telescopes in about 1625, one, in a silver tube, being for Henri-Louis Habert de Montmor an amateur of science, Cartesian and friend of astronomer Pierre Gassendi. The circle of friends who met in his study was the precursor to the Académie des Sciences. In his leaflet of 1625 entitled 'Les admirables lunettes d'approche réduites en petit volume avec leur vray usage',[111] he refers to these binoculars. They consisted of two spy-glasses, with convex objectives and concave oculars, fixed at an adjustable distance apart on a plate. Chorez claimed that they served both for distance and close magnification. The chemist, physician and botanist Pierre Borel named Chorez in his *De vero telescopii invento* of 1655 as one of the practical opticians who best succeeded in polishing lenses. The alchemist Erasmus Rasch wrote from Paris to Samuel Hartlib during the summer of 1655, mentioning Chorez and his instruments.[112]

In the 1620s, the mathematician Claude Mydorge introduced Guillaume Ferrier to René Descartes, also a mathematician. Ferrier was an educated man said to be a skilled mechanic, knowledgeable in optics and theoretical mechanics and professor at the Collège Royal in Paris. The three men worked in collaboration such that, around 1627, they managed to produce a hyperbolic lens.[113] The relationship between Ferrier and Descartes lasted some ten years but was frequently unharmonious. Ferrier resisted Descartes' invitation to join him in Holland while Descartes was dissatisfied with Ferrier's work, and his inability to grind hyperbolic lenses to Descartes's specification. By the 1660s and 1670s, when the Académie Royale des Sciences, and later, the Paris Observatory, were in existence, other opticians were available to serve the astronomers connected with it.

Chorez and Guillaume Ménard, both makers listed by Felipe Buonanni in his *Musaeum Kircherianum,* were certainly associated with the Capuchin monk known as Chérubin d'Orléans. Born Michel or François Lasérré in 1613, the son of a mercer of Orléans, he took the habit aged fifteen and thenceforth devoted himself to the study of mathematics and optics. He was a sufficient mechanic to make some of his own apparatus, items he then presented to the king, and he strove to perfect the binocular telescope designed by his confrère Schyrlaeus de Rheita. In later life he retired to a convent at Tours where he died in 1697.[114] Chérubin published in 1691 what he disarmingly referred to as his 'little treatise', a massive 400-page folio volume, *La Dioptrique Oculaire*, dedicated to the French general of finance, Jean-Baptiste Colbert. In *La Dioptrique* he explained that the cost of making long

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[111] D. Chorez, *Les admirables lunettes d'approche réduites en petit volume avec leur vray usage ...* , Paris, (1625). I am indebted to A. J. Turner for supplementary information on Chorez.

[112] Rasch to Hartlib, 22 May 1655, 17 July 1655. **HP Letters** 26/41/2A; 26/89/15A–16B.

[113] F. J. Dijksterhuis, 'Constructive thinking: A case for dioptrics' in L. Roberts, S. Schaffer and P. Dear (eds.), *The mindful hand: Inquiry and invention from the late Renaissance to early industrialisation*, Amsterdam: Koninklijke Nederlandse Akademie van Wetenschappen, (2007), 59–84, on 62.

[114] C. Brainne, J. Debarbouiller, Ch. F. Lapierre, *Les hommes illustres de l'orléannais*, vol. 2, Orléans: A. Gatineau, (1852), 29–30.

telescopes was beyond the means of one in his profession (that is, those in the religious life) and that this prompted him to learn to make telescopes for himself and his friends. Scorning the common artisan who polished his lenses on a simple suspended rod, he described his horizontal-axis lathe, with the tool being guided across the workpiece by hand.

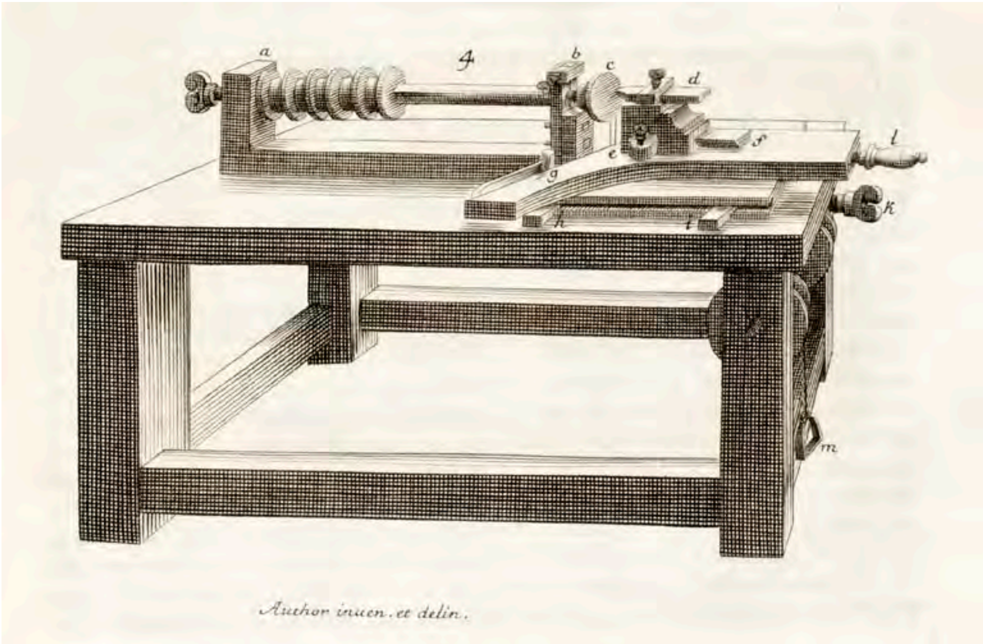

Figure 21: D'Orleans's turret lathe for working larger objective lenses. The operator can select from a range of tools of varying circumferences, according to the desired curvature. The striking characteristic of this design is the development of an articulated "turret" for holding the cutting tool, or in some cases the work itself. These complex devices have a range of motions (by mean of pivot, set screws and worm gears), and enable the work of cutting a form (or positioning the work against a form) to be carried out by means of the manipulation of an established set of mechanical parameters. In this sense, these systems represent some of the very earliest precision grinding systems, where the work is controlled by a fully articulated rest.[115] Chérubin d'Orleans, *La dioptriqve ocvlaire*, Paris: Chez Thomas Jolly & Simon Benard, 1671, plate 59, figure 4. © Whipple Library, Cambridge, STORE 69:4.

Peiresc was a member of his regional parliament in Aix-en-Provence as well as an amateur astronomer and mathematician and associate of Galileo while in Padua in 1600. He was in London in May 1606, attached to the embassy of Henry IV of the House of Bourbon, where he was introduced to King James I of the House of Stuart and those in parliamentary and scientific circles before continuing to the Low Countries where he was in Middelburg, Dordrecht, Rotterdam and Leyden.[116] When Galileo's published observations of Jupiter's satellites reached him, Peiresc

[115] D. G. Burnett, *Descartes and the hyperbolic quest: Lens making machines and their significance in the seventeenth century*, Philadelphia: American Philosophical Society, (2005), 116.

[116] G. Cahen Salvador, *Un grand humanist: Nicolas-Claude Fabri de Peiresc*, (1951). **Bibl. Inguimbertine**, Peiresc (1809) f.245, 288, 435, catalogued as the journal of Peiresc's time in England is brief and unhelpful.

at once sought to obtain a telescope. It seems that he was able to buy perspectives of some kind from Italy, Holland and Paris, as soon as they began to be made there, certainly by November 1610, for his first observations survive.[117] Peiresc's brother sent him some forty glasses from Paris. In later years he experimented with the images produced by variously figured lenses and mirrors, his colleagues in these experiments being Gassendi, Giovanni Alfonso Borelli, Jean Lombard and Bovis. Peiresc came to know of Cornelis Drebbel through meeting Jacob Kuffler in Paris, and he composed a 'life' of Drebbel.[118]

The Académie Royale des Sciences collected its first astronomical instruments in 1666, which included a range of telescopes from seven to thirteen feet in length, and in 1667 telescopes were substituted for the sight pinholes on their quadrants. Intendant Général des Fortifications and a savant of Mersenne's close circle, Pierre Petit loaned the Académie mirrors and a lens of 8½ inches in diameter. The mathematician and academician, Adrien Auzout, claimed to make lenses as good as Giuseppe Campani's, grinding them by hand, rather than on the lathe. Campani's work was recognized to be excellent and had won him the patronage of eminent figures such as Archduke of Tuscany Ferdinand II de' Medici, Cardinal Francesco Barberini, and Giovanni Domenico Cassini at the Royal Observatory at Paris. Auzout together with Pierre Borel made lenses for sale within their circle. In 1665 Auzout's dispute with Robert Hooke over the practicality of Hooke's proposed lens grinding machine filled many pages of the early transactions of the Royal Society and the Académie des Sciences before the German born scientific correspondent and secretary to the Royal Society, Henry Oldenburg, was able to smooth the ruffled feathers; several of Auzout's letters to Oldenburg refer to the various amateur and professional lens grinders then toiling at their benches, and the problem of getting optical quality glass worthy of their efforts.

Figure 22: Four-draw refracting telescope, by Guiseppe Campani, Italian, circa 1680, © Whipple Museum, Cambridge, Wh.1591.

[117] P. Gassendi, *The mirrour of true nobility the life of Peiresc*, translated by W. Rand, London, (1657), 2, 97–101, 144.
[118] Peiresc 1776, [Life of Drebbel]. **Bibl. Inguimbertine.**

In 1671, with the new Royal Observatory under construction in Paris, Colbert wrote to Cardinal César d'Estrées in Rome, asking him to negotiate with Campani and the instrument maker Eustachio Divini for the supply of telescopes for Cassini, who had been persuaded to move from Bologna to take up the post of astronomer. Campani had by this time gained a reputation even above that of Divini for the excellence of his lenses. Problems of production and the consequent delays for the buyer emerge from their letters, most of the originals being in the Archives de la Marine. D'Estrées was to persuade Campani to undertake a telescope half as long again as his most recent production, which had a focal length of fifty-five palms—that is, thirty-six or thirty-seven Paris feet. The king would reward his success and, wrote Colbert, if Campani cared to divulge his method of working lenses, he would be further rewarded.[119] Campani, however, preferred to labour in complete secrecy. His methods only came to light many years after his death, and then only in part. They are therefore discussed in a later chapter.

By January 1672 Colbert was yearning for a telescope of one-hundred and twenty palms, then under way in Divini's workshop. We get a glimpse of happenings from d'Estrées' letter of February:

> I have not seen Campani for some time, doubtless he will contact me when he has finished; as for Divini, he started work on a glass of 120 palms, which was broken in the operation. He wishes to begin again, and has hopes of success, meanwhile he is preparing the oculars for the telescope of 70 palms, which I told you of, which he believes to be more perfect than the others. We shall test it this week and I will let you know the result.

In September he was optimistic that the one-hundred and twenty palm lens would succeed, for Divini's workmen were talking with greater confidence, and d'Estrées was urging them on with the prospect of a reward.[120] By the summer of that year d'Estrées was urged to send the two instruments of fifty palms focal length which had been prepared, and the commander of the galley which was to ship them to France was commanded to hand them over to Cassini, who was at that time in Provence, for trial.[121] Cassini reported in November that the telescope, with its four glasses, had been tried on land and in the heavens, to his satisfaction. In June 1673 Colbert was again writing to d'Estrées:

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[119] Colbert to D'Estrées, 10 September 1671. in P. Clément (ed.), *Lettres, instructions et mémoires de Colbert*, vol. 5, Paris: Impr. imperial, (1868), 315–6.
[120] D'Estrées to Colbert, 9 February, 12 April and 14 September 1672, in G. B. Depping (ed.), *Collection de documents inédits sur l'histoire de France,* vol. 4, (1855), 582–3, 585.
[121] D'Estrées to Colbert, 13 July 1672, in *ibid.*, 584–5; Colbert to D'Estrées, 5 August 1672; Colbert to Arnoul, 16 September 1672, in P. Clément (ed.), *Lettres, instructions et mémoires de Colbert*, vol. 5, Paris: Impr. imperial, (1868), 332, 334.

> [...]regarding the telescopes, it is true that Divini has sent two glasses, but whereas Campani has sent only one, it was accompanied by its tube; on trial, they were equally good, and I hope that the payment they received will encourage them to further perfect their skills. As you know the French to be great imitators, I can tell you that we have here two Frenchmen, one, Borel, is known to you, who provides as many telescopes as we need. He has already supplied one of 50 feet and promises to make them of whatever length we desire; the other man has made one of 63 feet, whose glass is superior to any we have seen till now[...][122]

Campani had a long wait for his reward. In 1685 Cassini wrote to say that he was going to Versailles that week, to urge payment. [123] It was finally authorized in February 1687 with '4000 livres for four large lenses which [Campani] sent in 1683'.[124] Despite the vaunted superiority of French opticians, Colbert appealed to his brother, Charles Colbert, Marquis de Croissy and French ambassador in London, to procure him the best spectacles available in England.[125] Optician Phillippe-Claude Lebas supplied lenses for the observatory in 1674 and 1675. Christiaan Huygens met him in 1672 and obtained permission to watch him at work, albeit without discovering Lebas's trade secrets.

The mobility of both religious and lay men of science, spread an understanding of the optics of various forms of telescope and microscope, and some facility with lens grinding, across most of civilized western Europe, though it penetrated England in a somewhat diluted and erratic manner. With the foundation of the Royal Society of London and the French Académie Royale des Sciences, regular communication was established, in the form of letters and in published communications. This exchange is examined in Chapter Six.

Trading between Italy, the Low Countries and England

The Dutch town of Middelburg faced the major English east coast ports and was connected by the continual fighting of English troops in the Low Countries during the early seventeenth century. News and examples of the spy-glass travelled fast via the scholars and military men who made frequent crossings between England and the Low Countries, visiting and corresponding with their fellows in Holland. The activities of John Dee, Thomas Digges, and William Bourne, all men interested in

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[122] Colbert to D'Estrées, 30 June 1673, in Clément *ibid.*, 350–1.
[123] Cassini to Campani, 13 August 1685, in J. Archenholtz (ed.), *Mémoires concernant Christine, reine de Suède*, vol. 2, Amsterdam: P. Mortier, (1751–60), Appendix, 150.
[124] J. J. Guiffrey, *Comptes des bâtiments du Roy*, vol. 2, Paris: Impr. Nationale, (1881–1901), col.1085.
[125] Colbert to Colbert de Croissy, 29 September 1673, in P. Clément (ed.), *Lettres, instructions et mémoires de Colbert*, vol. 7, Paris: Impr. imperial, (1873), Private letters, 72–3.

mathematics, gunnery and astrology, testify to an excitement in optical matters equal to that in Europe.

Thomas Harriot was a mathematician and natural philosopher with particular interest in navigation, astronomy, and pipe tobacco smoking. He is credited with the introduction of this last to England from Virginia. He conducted his research from Syon House, Isleworth, under the patronage of the controversial Ninth Earl of Northumberland, Henry Percy. It was while based at Syon House that Harriot wrote to the politician and natural philosopher Sir William Lower in the autumn of 1609, sending him a small Dutch spy-glass. Lower reported back on the glass in early 1611:

> I have received the perspective cylinder that you promised me and am sorrie, that my man gave you not more warning, that I might have had also the 2 or 3 more that you mentioned to chuse for me.[126]

Lower then described those lunar features which he had been able to see for the first time, though he admits that a young companion was able to see them with the naked eye, indicating a low power of magnification. The companion was John Protheroe de Hawksbrook, or John Prydderch later to be one of Harriot's mathematical executors. This is one of the earliest examples of the import of spy-glasses from the Low Countries.

On 4 February 1609/10, some eighteen months after the supposed invention, Lyonell Wake, a merchant of Antwerp, wrote to William Trumbull, ambassador to the Archduke Albert of Austria in the Low Countries:

> […] upon the receipt of your letters I went about your perspective glasses with an intention to have brought them presently but the party held them so dear that I was half afraid to meddle with them, not knowing whether they will content you or not, and therefore after some days persuasions I have so dealt with the party that I have only taken them upon your liking, the which you shall return here within a box being four in all, viz., 3 of glass which are at 10s sterling the piece and one of crystal at 20s which is the lowest price I can get them at. You may take what you please and send the rest or all of them back to be here upon Monday for so I have promised.[127]

[126] A. Mee, 'Carmarthenshire and early telescopes', *Transactions, Carmarthenshire Antiquaries Society*, 4, (1908–9), 43–4. The letter is dated Treventi, 6 February 1610. Lower's use of Old Style dates brings it into the year 1611. Confusion arises, however, because the letter of 6 February, BL Add 6789 ff.427–8, appears incomplete and does not include the information quoted above.

[127] Wake to Trumbull, 4 February 1609/10. **Downshire.** 2, 228, Letter XLV.6

A second letter, dated 12 February, reports:

> [...]I have also received the crystal perspective glass which I have redelivered and have so dealt with the party here for the other three which you have kept that he hath rebated me 18 stivers in all off the 30s the which sum I will find good in the estuy you shall cause to be made[.][128]

The recipient of these purchases was Captain Edmond Brus (sometimes spelt Bruz), in London, who wrote to Trumbull on 14 February,

> [...]I thank you for your pains etc. ... in sending me the three perspective glasses, the which be very dear if they did cost 40s as you write, for they are not much better than I received first from you that cost but 4s as you write me. Notwithstanding I will not that you do lose anything. Yet if the party you had them of will be contented with a crown I will send them to him again and a crown over, or I will give him 10s for one of them or 20s for the three, but howsoever you shall not lose by me and at your next letter I will give the money to Mr Beaulieu. Your 'bieke' [sic] that you sent me I gave to my Lord Treasurer and also your first glass.[129]

Some commission seems to have been added to the price.

The identity of Captain Brus is uncertain. Among the Trumbull manuscripts in Salisbury is a list of books in Italian with the following note:

> All these parcels were sent to the right worshipful Sir Charles Davais Kt., as true owner thereof, by me Edmond Bruz, being delivered to Mr Thomas Barnes, part owner and purser of the 'Gallion Sutt' ship of London in Venice the 18th of November 1593.

Three letters now in the Osterreichische Nationalbibliothek in Vienna, are known from a Brus to Johannes Kepler between 1602 and 1603. With a further letter from Kepler to Brus, dated 1603 in the British Library.[130] One from the Vienna collection dated 15 August, to Prague, directs Kepler to send his replies to David Hoeschel, Rector of the Gymnasium bei St Anna in Augsburg, who would forward them. An Edmondo Bruzio is also noted several times as being among those friends of

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[128] Wake to Trumbull, 12 February 1609/10. **Downshire.** 2, 229, Letter XLV.7. The stiver was a small coin current in the Low Countries. The estuy was probably the box mentioned earlier.

[129] Brus to Trumbull, 14 February 1609/10. **Downshire.** 2, 239, Letter Misc.II.45.

[130] Brus to Kepler, 15 August 1602 from Florence, 21 August 1603 from Padua, and 5 November 1603 from Venice, Osterreichische Nationalbibliothek in Vienna; Kepler to Brus, 4 September 1603, **BL. Lans.** ms 89.15.

Galileo who frequented his house at Padua in the early 1600s.[131] It is possible that Edmund, or Edmond; Brus, Bruz, or Brutius, are the same individual.

If this identification is correct, the man involved in importing these spy-glasses into England was already familiar with astronomy and optics as practiced in Central Europe. Beyond this, he remains a shadowy figure. Another message, this time to Trumbull and dated 9 December 1612, is concerned with a letter and three pairs of spectacles sent from the Gaston Spinola, Count of Bruay which had gone astray. This letter discloses that Brus 'is now lodged in the Strand in Mr Millington's house near St Clemans'.[132] His may be the Will found for Edmund Bruz, resident in the parish of St Clement Danes at the time of his death in February 1617—just a few lines bequeathing everything to an unnamed brother. The last word was that of correspondent John Chamberlain to the art collector and diplomat Sir Dudley Carleton, 18 October 1617, 'Captain Brus died sodainly not long since[...]'.[133]

The emergence of a London workshop

The spy-glasses with which Trumbull and Brus were concerned were made overseas. The first evidence of telescope manufacture in England comes in Thomas Harriot's works. Harriot was experimenting with prisms and calculating refraction angles by 1597.[134] His maps of the moon, as he observed it on 26 July 1609 with a telescope that magnified about six times, represent the first such record in England.[135] The provenance of his first telescope is unknown, but at some point Harriot employed Christopher Tooke and set him to grind lenses and prisms for his optical experiments; they also observed together. Tooke came from the numerous landed family of Tooke of Essendon in Hertfordshire, many of whom were in the service of the Cecils of nearby Hatfield House.[136] Northumberland household papers indicate that he came into Harriot's service in late 1604 or early 1605, and became Harriot's right-hand man at Syon House, taking observations with him.[137] There is no information as to where Tooke learnt this skill or where the glass was obtained, nor do we have any details concerning the manufacture of lenses. Another letter from Sir William

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131 A. Favaro, *Amici e correspondenti di Galileo,* Venice: C. Ferrari, (1902–16), vol. 2, 12 and 621; vol. 3, 1545.
132 Brus to Trumbull, 9 December 1612. **Downshire.** 3, 432, Letter, Misc.IV.133. 7.
133 **Cal. SPD**. James I (1617), 93.
134 Harriot has been credited with the rediscovery of the critical law of refraction, published in Arabic in 984AD. Now known as Snell's Law, after a subsequent discoverer, it states that the ratio of the sine of the angle of incidence to the sine of the angle of refraction is a constant for any pair of media.
135 J. W. Shirley, 'Thomas Harriot's lunar observations', *Studia Copernica,* 16, (1978), 283–305.
136 R. Clutterbuck, *History of Hertfordshire* (3 vols., 1815–27) vol. 2, 134–5, 137, 351–2.
137 I am obliged to Professor Gordon Batho for this information.

Lower to Harriot, dated 'longest day of 1610',[138] reminds Harriot

> [of] your promise to send me of all sorts of those cylinders - my man shall deliver you money for anie charge requisite and compensate your man for his paines and skill - send me as many as you think needful.

Figure 23: Detailed moon map, six inches in diameter, drawn by Thomas Harriot, from observations through a telescope. The map was possibly built up from phase drawings and probably made between 1610 and 1613.[139] Bestiasonica, https://ungaman.wordpress.com/2009/01/17/¿que-es-lo-que-celebramos-en-el-aia-2009/, CC-PD-Mark.

The man referred to may well be Tooke. In his Will, Harriot bequeathed various optical glasses and telescopes to his friends,

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138 Lower to Harriot, [21 June] 1610. **BL** Add. 6789 ff.425–6.

139 For further information see A. Chapman, 'A new perceived reality: Thomas Harriot's Moon maps,' *Astronomy and geophysics*, 50 (1), (2009), 1.27–1.33.

> and to my servant Christopher Tooke the residue of my cases of perspective trunkes with the other glasses of his own making fitted for perspective trunkes[...] Also I bequeath the dishes of iron called by the spectacle makers tooles to grind spectacles, and other perspective glasses for trunkes unto my foresaid servant Christopher Tooke.[140]

How familiar such instruments had become by 1610 is indicated by references in the existing correspondence. Astrologer Christopher Heydon, wrote to the antiquary William Camden on 6 July 1610, that '[o]f my own experience with one of our ordinary trunkes I have told eleven stars in the Pleiades, whereas no age ever remembers above seven[...]'.[141] Writing to Harriot in July 1611 about the satellites of Jupiter, William Lower's note that 'onlie with your great glass could I see them in London' clearly refers to a telescope. Thomas Aylesbury, a friend of Northumberland who also patronized mathematics, wrote to Harriot on his return from the Low Countries in 1613, 'I must not forgett to tell you, your glasses have fitted my Lord excellentlie well[...],' though this could equally refer to spectacles.[142]

The problems associated with the supply of spy-glasses is brought out in a letter from the politician Sir Robert Killigrew to Sir Dudley Carleton, then HM Ambassador at The Hague and the same who was informed of Brus' death. On 14 September 1618, Killigrew wrote the following in a note accompanying a perspective glass:

> 'Sir, the falcewood [falsehood] and unskilfulness of workmen who besides their promice breaking, have ground me forty glasses before I could have such as would serve, hath been the cause I have staed so long from performing my promice which I have now at last don by sending you a perspective glass[...]'[143]

Here it is apparent that a spy-glass made in England is being exported to the Low Countries. The following table, adapted from Eleanor Godfrey's work *The development of English glassmaking 1560–1640*, gives the quantities of spectacles shipped in or out of London. The changes revealed point to the establishment of a domestic craft using the 'spectacle plates' of glass-maker Robert Mansell

140 Harriot's Will is reproduced in H. Stevens, *Thomas Harriot, the mathematician, philosopher and scholar*, London, (1900), 193–203. 'Trunkes' are the telescope tubes.
141 Heydon to Camden, 6 July 1610. In W. Camden, *Epistolae*, (1691), letter 89.
142 Lower to Harriot, 4 March 1611. **BL**, MS Add. 6789 vol.viii, f429^{V}; Aylesbury to Harriot, 15 April 1613. **BL** Add. 6789 vol.viii, f.439.
143 Killigrew to Carleton, 14 September 1619. **Cal. SPD.** James I, 110 (1619–23), f.92 (orig. f.98).

discussed in Chapter Two.[144]

Spectacles shipped into London.

Date	gross	£.	s.	d	Origin
1567/8	40	20.	0.	0	Flushing, Antwerp
1587/8	75 ½	37.	10.	11	Hamburg, Rouen, and Stade
1609	39 ½	19.	15.	0	Stade
1621	16	8.	0.	0	Hamburg
1626	4	2.	0.	0	Amsterdam
1630	2	1.	0.	0	Middleburg
1640	None		-		-

Spectacles shipped out of London.

1634	13	6.	10.	0	Hamburg, Dunkirk
1640	21 ¾	10.	17.	6	Canary Islands, Amsterdam, Dieppe, Portugal, and Robordence

Table 1: adapted from 'Spectacles shipped in or out of London', in E. S. Godfrey, *The development of English glassmaking 1560–1640,* (1975), 242, Table 10.

One consumer of those spectacles, whose frequent purchases have been recorded, was William Howard of Naworth Castle, who paid 3s for 'two payre of spectakls' in 1627, 2s 6d for 'setting one payre of spectacles in silver' in 1629, and many more pairs, including one fitted with green glass, to cater to his deteriorating sight in later years.[145]

Few names of the craftsmen grinding these lenses have come down to us, the first identifiable optician being a 'Mr Bates' who offered navigational instruments and perspective glasses at Tower Hill. His wares were advertised by the English soldier, explorer and author, Captain John Smith in his pocket-book *An accidence or the path-way to experience necessary for all young sea-men*, published in London in 1626.[146] In 1628 the British fleet; sailing under the command of Robert Bertie, Earl of Lindsay, to relieve the Huguenots at La Rochelle; were said, while at anchor outside the blockaded harbour, to have watched events ashore through their telescopes. The very title of Edward Cooke's small text-book on military training, *The prospectiue glasse of warre* (1628), assumes some familiarity with the spy-glass, and by implication, with its suppliers.[147] Cooke was an amateur

[144] E. S. Godfrey, *The development of English glassmaking 1560–1640*, Oxford: Clarendon Press, (1975), 242.
[145] George Ornsby (ed.), *Selections from the household books of William Howard of Naworth Castle*, Surtees Society, 68, (1878).
[146] J. Smith, *An accidence or the path-way to experience necessary for all young sea-men*, London, (1626), 49.
[147] E. Cooke, *The prospectiue glasse of warre*, London, (1628).

military enthusiast who had spent four years training with the London Middlesex Company in the early 1620s. *The prospectiue glasse of warre* was the second of two short analytical treatises written at the height of the Caroline conflict with Spain. It is considered by military historians to be representative of some of the worst writing that English military authors had to offer.[148]

In July 1628 Robert Alte, a freeman of the Brewers' Company but a spectacle-maker by trade, petitioned King Charles I of the House of Stuart on behalf of a group of spectacle-makers, requesting a charter for the formation of a company dedicated to their craft. His petition was granted and the Spectacle-makers' Company was duly chartered in May 1629, being empowered to bind apprentices and to regulate trade within the City of London. Thirteen spectacle-makers were translated from the Brewers' into the new Spectacle-makers' Company, several of these men, like Robert Alte, having been apprenticed from the same village, namely Shepshed in Leicestershire, and others having come from the surrounding district.[149] Unfortunately the earliest records of this guild were lost in the Great Fire.

<u>The craftsmen are joined by mathematicians</u>

In May 1638 the astronomer Jeremiah Horrox bought a telescope for half-a-crown and observed the partial solar eclipse and the transit of Venus of 1639. By October 1640 the mathematician and astronomer William Gascoigne possessed a Galilean telescope nearly forty-five inches in focal length, with plano-convex objective and plano-concave ocular, of 'London best sale glasses.' Gascoigne's measurements show that the objective was approximately two and a quarter inches in diameter, and of slightly denser glass than the eyepiece. Gascoigne was interested in optical theory and experimented with various convex lenses for perspectives and for spectacles. Living in Yorkshire, he voiced his regret that he had no workmen to assist in making lenses or fittings.[150] Horrox's telescope, from its low price, appears to have been a small instrument, but in London by this time serious attempts were under way to obtain larger and better telescopes. In October 1634 Walter Warner, mathematician and natural philosopher, was writing to the natural philosopher Robert Payne that he was compiling a table of

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148 D. Lawrence, *The complete soldier: Military books and military culture in early Stuart England (1603–1645),* Leiden: Brill, (2009), 216.

149 G. Clifton, 'The Spectacle-makers' Company and the origins of the optical instrument-making trade in London', in R. G. W. Anderson, J. A. Bennett and W. F. Ryan (eds.), *Making instruments count: Essays on historical scientific instruments presented to Gerard L'Estrange Turner*, Aldershot: Variorum, (1993), 341–364, citing the original documents at Guildhall Library.

150 S. B. Gaythorpe, `On a Galilean telescope made about 1640 by William Gascoigne, inventor of the filar micrometer', *Journal of the British Astronomical Association*, 39, (1928–9), 238–241; Letter, Gascoigne to Oughtred, February 1641, in **Rigaud.** vol. 1, 35.

refractions for glass and crystal.[151] Warner and Payne belonged to the same intellectual circle that included mathematicians John Pell and William Oughtred; the philosopher Thomas Hobbes; and was fostered by the Cavendish brothers: William, a military officer and first Duke of Newcastle upon Tyne; and Charles, the younger brother and talented mathematician. Given the variability of manufactured glass, Payne's efforts are unlikely to have borne much fruit, nonetheless, in September 1636 Charles Cavendish wrote to Warner to thank him for sending tracts on images in concave and convex glasses and on making prospective glasses.[152]

Warner had entered the service of Henry Percy, in 1590. His duties concerned the purchase and care of the earl's books and scientific instruments. He was thus a colleague of Harriot who was also attached to the earl's household at Syon. While Percy was imprisoned in the Tower, between 1605 and 1621, Warner joined in the learned discussions of the Earl and his other mathematical clients. After 1620 Warner lived at the Woolstaple in Charing Cross, Westminster, and at Cranborne Lodge near Windsor, with Aylesbury, who sponsored his continued work on optics and mathematics. After the earl's death in 1632 his son discontinued Warner's pension. From then until his own passing Warner worked over Harriot's papers and collaborated with Pell, and in 1635 he sought the patronage of the Cavendish brothers. To the latter he sent tracts on telescope construction and concave and convex glasses, receiving a reward of twenty pounds for his efforts. In later years Hobbes replaced Warner as a Cavendish client and despite the assistance of Aylesbury, Warner died, unmarried and in poverty, in 1643.

Sir Charles Cavendish had travelled in France and represented Nottingham in parliament before inheriting estates that allowed him to devote himself to mathematics and the patronage of mathematicians.[153] He collaborated with Pell and Warner on the subject of optics and telescopes. The optician to whom they turned to obtain their lenses was Richard Reeve (whose contemporaries spell as Reeves, Rives, Reaves). Men from a range of backgrounds resorted to Reeve's shop by 'The Foot and Leg' public house in Long Acre: from the polymath Christiaan Huygens, through mathematician James Gregory, natural philosopher Robert Hooke, antiquary and astrologer Joshua Childrey, naval official Samuel Pepys, to the judge Thomas Street. Trading outside the City of London, he does not appear to have been a freeman of any guild.

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[151] Warner to Payne, 17 October 1634. **BL**, MS Add. (Birch) 4444 f.93.Payne had been a student at Christchurch Oxford in 1616/17. He later became chaplain to the Cavendish family at Welbeck Abbey and translated for them several texts of Galileo.

[152] Cavendish to Warner, 2 September 1636. **BL**, MS Add. (Birch) 4444 f.91.

[153] J. Jacquot, 'Sir Charles Cavendish and his learned friends', *Annals of science*, 8 (2), (1952), 13–27.

Reeve and his workmen were pushed to the limit of their capabilities by Charles Cavendish's demands; but the nobleman mathematician himself noted that limitations of skill were not the only obstacles when he wrote to Pell in 1641:

> I perceive our business of making the perspective glasses proceeds not and I know not well howe to help it unless there be some good matter to make glass, in some other place to be bought, for it seems that, at Broadstreet, will not be had: I am not willing to trouble Sir Robert Mansfeild [*sic*; Mansell is surely intended] about it, though I think he would not denie me. Therefore if you or Mr Reaves can find fitting matter for us somewhere else, you should do me a greate favoure. Broadstreet I suppose will be the best place to make the glass, when you have bought the stuffe to make it of. I shall write to Mr Reaves to give us his help therein.[154]

Materials and environment were constant significant factors alongside social and political concerns.

The problems of obtaining good glass continued to bedevil them; in July Charles Cavendish responded to a letter from Pell that had crossed with his previous one:

> your letter dated June 26th came not to my friends till the 10th of this month when Mr Reaves sonne brought it to my house in St Peters Streete (for I am removed) with a piece of glasse made at Broadstreete if we may believe the spectaclemaker of whom Mr Reeves bought it[...] I suppose others have sent you word that the workmen being overcome with the importunities of our men and some spectaclemakers, did at length prepare a pott of choice mettal as they speake, but for want of skill or care, over fired their worke and brake their pot, and then was all the fat in the fire, their Lady [this was Lady Mansell] so heated she will not hear of giving them leave to make a new adventure, so Mr Reave found out this piece, but he having lost the former patterns, I drew 4 more and [in margin: `July 12'] he went with your goldsmith to a cutter of gemmes who promised to despatch them speedily. The last Saturday [in margin: `July 17'] Mr Reave went to his house and found a journeymen ready to polish them up, having no squire or other direction more than my draught, to examine them by. He caused him to lay them aside and sent me word of it, this morning and [in margin: `July 19'] we have been with the workman, he promised to finish them himself accurately by a squire which Mr Reeve is to send him. I am now come back from there to your goldsmith's shop here to write this answre: Mr Reeve desires to be excused for not writing, having lately so overwrought his hand he cannot hold a pen. He says he hopes to have the

[154] Cavendish to Pell, 26 June 1641. **BL**, MS Add. 4278 f.161.

> perspective finished by Michaelmas [29 September].[155]

By the following week Charles Cavendish learnt that a suitable piece of glass was now in Pell's hands:

> I am glad to learn you have got some glass, I hope it is good and fit for our purpose, for I should be unwilling that you and Mr Reaves should bestow your paines upon coarse glass. When you have tried what the refraction is in that glass I desire to know it, and also how you like the glass.[156]

Pell explained that Reeve's workman had almost finished grinding the lens to the squire or pattern which Reeve had given him when Reeve had procured a clearer piece of glass and ordered the man to begin anew. Pell had called on a mathematical joiner and instructed him to prepare a ruler such as Descartes had illustrated on page 137 of his book, though Pell does not say which book, but 'more convenient and so more costly'; this was promised for the following week. At the same time four triangles, that is, prisms, were to be made ready. All these items were necessary for Pell's trials on refraction of the lenses.

> Yours of July 24 requires no answer till we have tried ye refraction which as yet we have not done but your Goldsmith calls upon me by this carrier to give you account of how far we are advanced. Mr Reeves helped [?] ye workman to a squire, with which when he had almost done the work he made him lay it aside and begin anew upon a cleerer piece that he had after met withall, this he despatched and sent them 4 days ago. I went next morning to a mathematical joiner and left directions for the making a reigle [ruler] something like that which Des Cartes describes pag.137 but more convenient & so more costly. He promised that I should have it in ye next weeke. In the meane time I wished ye Goldsmith to give order to ye workman to finish ye 4 former triangles also seeing he must be paid for his worke (though not finished) when we have it we may try the difference of these two sorts of glasses & accordingly proceed. Mr Reeve longs to do work upon them[...][157]

The grinding was a slow process. Two glasses had been ordered, a convex to be shaped into a hyperbolic curve, and a concave lens. Before work commenced on the latter, Cavendish asked Pell to see if his own concave glass would fit with the new convex lens:

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[155] Cavendish to Pell, 19 July 1641. **BL**, MS Add. 4278 f.165.
[156] Cavendish to Pell, 24 July 1641. **BL**, MS Add. 4278 f.163.
[157] Pell to Cavendish, 9 August 1641. **BL**, MS Add. 4278 f.165v.

> I hope Mr Reaves is in a good forwardness with the convex glass; I dout not but you will try all conclusions with it, which may condiuce to inform you whether it be a hyperbole or no; as also what proportion the diameter of the glass hath to the line of contracted beams of the sun at the point of concourse; as also to observe, what aparences are made, the eye being placed in, before or behind, the pointe of concourse; and in the meantime, before the concave glass be made, to try whether my concave glass, which you have, will in any sort fit it. Sir, I leave the further scrutiny of this to your better consideration, and wishing you all happiness, remaine ... [PS] I pray you commend me to Mr Reaves when you see him.[158]

Reeve continued to make slow progress; by December the convex lens was still in preparation, indeed it seems that the weather was partly to blame for the delay, and Cavendish was becoming impatient:

> I thank you for your letter of December 13. I am glad Mr Reeves is so well fitted for our work; when he hath done it, I dout not but you will make all such trials as may be give you satisfaction whether it be a true hyperbole or not, and then proceed to the making of the concave glass; if this fit it not, I shall still be in hope that a concave on both sides will[...][159]

But in February 1641/2 Cavendish was obliged to warn Pell that 'Mr Reaves hath now broken in his triall so much glass that I doubt there is none left of that which you had tried your refraction in[...].[160]

Political events in the shape of the Civil War brought to an end these trials, which might well have advanced the development of telescope lenses. The Cavendish brothers entered the king's service in 1642. Charles behaved with great gallantry, distinguishing himself at Marston Moor in 1644. After that battle, despairing of the royalist cause, the brothers took ship for Hamburg, travelling in the following year to Paris and The Hague. Charles subsequently endeavoured to retrieve some of his confiscated estates, to provide an income for his brother's otherwise impoverished family, but these negotiations were not completed when he died in February 1653/4. Pell took up the chair of mathematics at Amsterdam in 1642, moving in 1646 to a new college at Breda. He returned to England in 1652; two years later he was sent to Geneva, from where he returned in 1658. Although he had held an appointment under the military and political leader Oliver Cromwell, some small service rendered to the royalist cause

158 Cavendish to Pell, 20 November 1641. **BL**, MS Add. 4278 f.139.
159 Cavendish to Pell, 18 December 1641. **BL**, MS Add. 4278 f.141.
160 Cavendish to Pell, 5 February 1641. **BL**, MS Add. 4278 f.136.

preserved his reputation and having taken holy orders, he held two preferments in Essex until his death. He retained his interest in mathematics and was included in the first list of fellows of the Royal Society in May 1663, but soon afterwards he fell into hopeless debt, from which he never escaped. He died in December 1685.

This section has reproduced correspondence in detail to underline an important point: the manufacture of a piece of clear and unstressed glass requires a mathematician who could ascertain its refractive index and thereby calculate the curvature of the lens; *and* the craftsman or men who could prepare the metal forms and grind the lens. It relied on the money to finance these operations at the same time as being dependent on a supply of the necessary raw materials. For glass production to advance with success demanded sociability alongside fastidious solitary work. It was a challenge that extended far beyond the significant obstacles of materials and methods to the climate: both meteorological and political.

Chapter Five
The practice of lens-making and its theoreticians

From the earliest period of lens manufacture it appears to have been standard practice to grind and polish lenses by rubbing the glass against a basin or 'former' charged with abrasive. The lens-grinder required concave and convex formers of various radii of curvature to match the figures of the lenses that he wished to make. That fifteenth-century Florentine spectacle-makers were able to meet orders for concave and convex lenses, the latter differing in curvature, implies they had a range of such formers to hand. Chapter Three related how the nobleman Johann Philip Fuchs von Bimbach and the astronomer Simon Mayr sent a plaster model of a desired lens shape to spectacle-makers in Nuremberg. The inability of the Nuremberg opticians to grind a lens that would correspond to the Fuchs and Mayr's pattern suggests that this particular order lay outside their normal range and they were either unwilling to go to the expense of constructing a special former which would have no further use, or that the plaster model was not spherical and they did not know how to deal with such an unfamiliar request. In his encyclopaedia of arts and crafts the Italian writer Tommaso Garzoni, explains that spectacles are categorized in terms of the diameter of the iron form, each of which makes a lens suited to a certain age.[161]

<u>Isaac Beekman's technique</u>

Isaac Beeckman provides one of the clearest descriptions of late sixteenth and early seventeenth-century spectacle-makers' workshop practice.[162] Beeckman, the son of a candle-maker at Middelburg, was studying mathematics and theology at Leiden when the spy-glass made its first appearance. He was in England, where he had relatives, in 1612 and again in 1616, but does not mention the state of optical glass-working in London. After an interlude working as a candle-maker in Zeeland, he embarked on the study of medicine and travelled to Caen in France in 1618 to obtain his doctorate. It was during his stay there that François-Gilles Macé, professor of medicine and mathematics, showed him a sketch of Galileo's telescope. On his return, Beeckman went to Breda and there met and became friendly with the mathematician and philosopher René Descartes

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[161] T. Garzoni, *La piazza universale di tutte le professioni del mondo*, Venice, (1585), 233^{v}–235^{r}.

[162] **Beeckman**, 'Vie de l'auteur', 1, i–xxiv; 'Introduction aux notes sur le rodage et le polissage des verres', 3, i–xiv; Notes ... 371–431.

(of whom more below), who was then on military service in the area. In later years the Minorite father Marin Mersenne, the Aix philosophy teacher Pierre Gassendi, and Gassendi's patron the gentleman astronomer Nicolas-Claude Fabri de Peiresc, each of whom are dealt with further in Chapters Three and Six, also called on him.

Keen to make his own telescope, Beeckman was shown by the astronomer Johan Philippe van Lansberge of Middelburg how to make a prospect glass with a biconvex objective and biconcave eyepiece. Such eyepieces could be obtained from spectacle-makers, but only with some difficulty as the eyepiece had to conform to the objective, and the available objectives lacked the necessary long focal length. In 1622 Beeckman had made one of these prospect glasses at Middelburg and in 1624 he had sought one at the Hague but neither exercise had been successful. It was only in 1632 that he began making a telescope. The difficulty of the work led those interested in its execution to take instruction from professional spectacle-makers. Beeckman mentions receiving guidance from experts in Dordrecht as well as, in 1634, instruction from the skilled lens-grinder Johannes Sachariassen of Middleburg, son of the spectacle-maker Janssen Sacharias (see Chapter Three); an unidentified Englishman at the Dam of Amsterdam; and the mathematician, surveyor and sheriff of De Bilt, Paulus Ruysch of Utrecht.[163] It is unfortunate there are no extant records of the craft practices of these men.

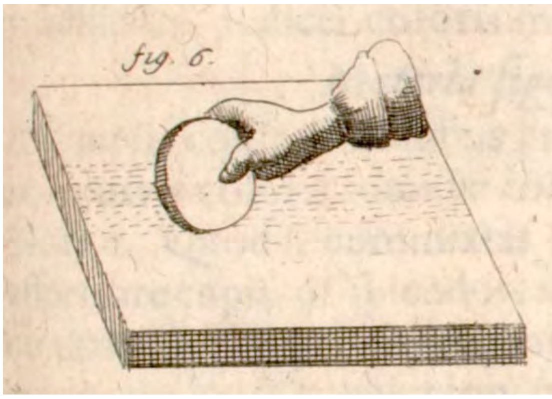

Figure 24: One consequence of grinding was a lens that tapers towards the rim. This tapering exacerbated chromatic aberration. To minimise the aberration lenses were trimmed and the edge ground smooth. Johann Zahn, *Oculus artificialis teledioptricus*, Herbipoli: Sumptibus Quirini Heyl, 1685-6, 'Fundamentum III', 'Practico-Mechanicum Fabrica', p.34, iconismus V fig 6. © Whipple Library, Cambridge, STORE 43:17.

Venice crystal was Beeckman's preferred material. It could be obtained as 'mirror glass' or 'venetian mirror,' which have been described in preceding chapters. It was clear, homogenous, colourless, free of bubbles and streaks, and was generally well-polished to a plane finish. Lenses could be cut from a piece of such sheet. The practice was to draw a circle slightly oversize and trim the glass

[163] H. J. Zuidervaart, 'The 'invisible technician' made visible: Telescope making in the seventeenth and early eighteenth-century Dutch Republic, in A. Morrison-Low, Sven Dupré, Stephen Johnston and Giorgio Strano (eds.), *From earth-bound to satellite: Telescopes, skills, and networks*, Leiden: Brill, (2012), 41–103, on 75.

with hot pincers. Beeckman made lenses of one and a half, two and a half and often three inches diameter.[161] He advised that the diameter should not be too great, in order to lessen the amount of chromatism around the periphery. This compensation against the problem of chromatism is explained in more detail below.

Figure 25: A series of factors encroached on the size of the lens produced. For example while the highly variable quality of the original glass meant lens blanks were necessarily small and taken from the piece with fewest defects, trimming to reduce chromatic aberration reduced the size still further (as in Figure 24). Johann Zahn, *Oculus artificialis teledioptricus*, Herbipoli: Sumptibus Quirini Heyl, 1685-6, 'Fundamentum III', 'Practico-Mechanicum Fabrica', p.34, iconismus VI fig 10. © Whipple Library, Cambridge, STORE 43:17.

The basins for shaping the biconvex lenses were cast of metal; normally iron, but copper, brass, and lead were also used. The spherical radius of the former needed to slightly exceed the focal length of the intended telescope. The larger the basin of the former the greater its spherical radius. Once cast, the basin was smoothed with care, either by filing, or by suspending a polishing stone from a point above the centre, and sweeping it around the basin. A suspended stone could be arranged to work on plane, concave or parabolic surfaces. As mentioned, mirror-makers also used this technique to polish flat mirrors. Some spectacle-makers performed their grinding 'freehand' but Beeckman preferred to work with a suspended stone. He employed an iron basin slightly over four Rhineland feet in diameter that is, 125.6 cm. The wooden handle was equal in length to the diameter of the lens to be worked, and the glass was fastened to its base with warm adhesive.

Grinding began with coarse sand or emery, though on occasion the latter might be too abrasive. The sand was continually dampened so that the glass slid easily across the basin. As work proceeded, finer grades of sand were introduced. Surplus sand had continually to be wiped away with a leather and great care taken not to leave a single larger grain behind lest it score the basin or the glass. The finest sand powdered and flew up, coating the workman's clothes in dust, so that care must be taken to keep hands and sleeves clean, to avoid any dirt

[161] These dimensions are presumably in Rhineland feet.

accumulating under the glass. The polishing handle should be weighted with lead as work proceeded so as to maintain a firm pressure. This often caused the handle to heat up, with the risk of softening and relaxing the adhesive. After days, or even weeks, of toil the glass began to shine and grinding gave way to polishing.

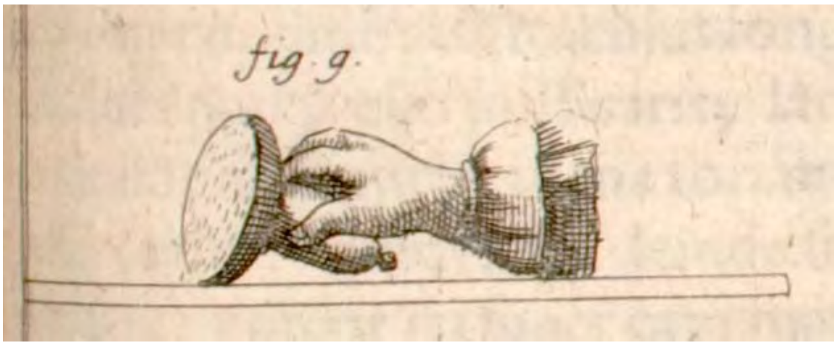

Figure 26: Diagram shows a lens-blank fixed using pitch or rosin to a short wooden or stone handle called a mollette. The tool was important in manual work to hold the lens-blank while shaping it on the form; and hold it while pressing down to be polished. However, the short handle and the wide distribution of force over the surface of the glass could lead to a rocking of the blank as it was guided over the form, resulting in distortions of shape.[165] Johann Zahn, *Oculus artificialis teledioptricus*, Herbipoli: Sumptibus Quirini Heyl, 1685–6, 'Fundamentum III', 'Practico-Mechanicum Fabrica', 34, Iconismus V, fig. 9. © Whipple Library, Cambridge, STORE 43:17.

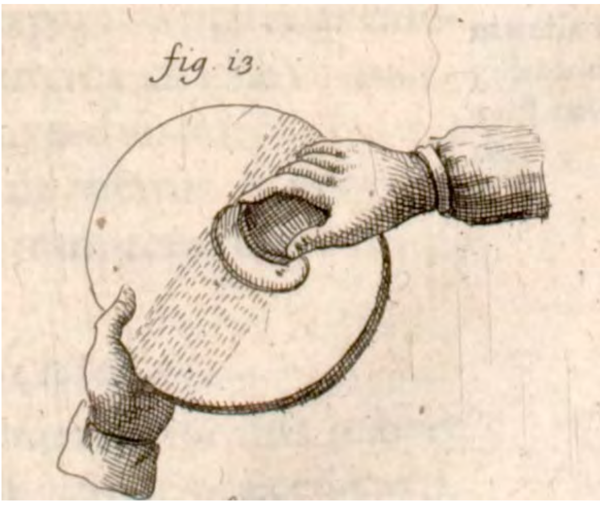

Figure 27: As the abrasive material used to grind and polish the lenses became increasingly fine, the dust would coat the lens grinder's hands and sleeves. Despite careful wiping between successive polishes, this stray abrasive risked scratching the lens. For manual work Zahn recommended holding the glass and plate vertically so that excess dust would fall away, reducing this risk. Johann Zahn, *Oculus artificialis teledioptricus*, Herbipoli, 1685–6, 'Fundamentum III', 'Practico-Mechanicum Fabrica', 34, iconismus V, fig. 13. © Whipple Library, Cambridge, STORE 43:17.

At this point the craftsman cleaned the basin and tools and then scored grooves in the basin with a file to receive the powder. Polishing was performed as before, with the handle suspended to control a spherical motion, or freehand. Wooden or stone basins were sometimes used at this stage. Beeckman preferred a brass basin, made slightly flatter than the previous iron one. Some material

165 D. G. Burnett, *Descartes and the hyperbolic quest: Lens making machines and their significance in the seventeenth century*, Philadelphia: American Philosophical Society, (2005), 96–8.

was often interposed between glass and basin. This could be leather, or any cloth that would not break up and shed fibres under the glass. Certain spectacle-makers omitted the cloth and polished on the iron basin. Johannes Sachariassen did this and Beeckman followed suit when he worked alongside Sachariassen. In short, the polishing tool was a matter of preference and personal technique. Beeckman is explicit that nothing can be set down as a general rule for much is left to the initiative of the workman. The first polishing powder was rouge, grading to tripoli, and lastly calcined tin, which was obtained from the cinders of tin smelters' furnaces. It would happen during the polishing that the lens curvature might change or the centre took a polish first, in which case the glass would need regrinding in order to bring it to the original intended curvature. Polishing could take from one to nine hours.

The procedure as Beeckman described it was followed by most lens-makers with only minor variations for personal preference. The exception was the introduction of the turn-bench or lathe, intended to ease the physical effort—and indeed the tedium—of grinding and polishing. This enabled several lenses of identical figure to be produced at the same time, or in sequence. Christiaan Huygens copied much of Beeckman's account into his own notebooks, along with drawings of the polishing machines.[166]

<u>The supply of optical quality glass</u>

At Middelburg Beeckman had access to one of the best crystal glass-houses of the day. Others were less fortunate. Common glass was useless for lenses as it contained too much sand, though its quality could sometimes be remedied by strong heating. Sachariassen remelted cullet for glass intended for telescopes; keeping it over a slow fire for several weeks to reduce the internal strains and consequent separation of refracted rays. Beeckman dismissed natural rock crystal as unsuitable because of its high reflective property. However, as seen in Chapter Four, it was one of the earliest materials employed in the manufacture of spy-glasses, and it continued to find favour, both for working directly and as the raw material to be crushed for vitrification. In particular it was the material of choice for astronomers in remote places who lacked a source of clear glass. For many grinders, however, both amateur and professional, broken mirror was the best material for lenses. It was of good quality while its polished surface was adequate for the plane face of a lens. Other glass was often remelted and cast into lentoids slightly larger than the desired lens, to minimise the effort of grinding it to shape. Garzoni asserted that German glass was soft and had most clarity, Murano glass was harder to work, and mountain crystal was the hardest

[166] C. Huygens, *Oeuvres complètes de Christiaan Huygens*, vol. 17, (1932), Figs. 21 and 24, on 299, 301.

of all.[167]

Long after its first publication, an English summary of Christiaan Huygens' techniques became available in the mathematician and benefactor Robert Smith's 1738 publication: *Optics*. Book Three, Chapter One of *Optics* treats of 'The method of grinding and polishing glasses for telescopes, extracted from Mr Huygens and other authors by the Hon. Samuel Molyneux'.[168] This Samuel was an astronomer; politician; and the third but only surviving offspring of the Dublin born experimental philosopher and constitutional writer William Molyneux, whose interest in practical optics is dealt with in a later chapter. Samuel, like Smith himself, was ignorant of lens grinding, and explained that his information was drawn from Christiaan Huygens, originally written in Dutch and translated into Latin.

According to Smith, Huygens recommended glass that was yellowish, reddish or greenish; the white glass generally being full of veins, and often prone to sweat, which destroys the polish. In his region, there had been no better material than looking-glass, until he found some of fairly good quality at a glass-house, made for drinking glasses. Huygens said that the glass was always better after it had been resting in the slowly cooling furnace over a holiday period. He took glass intended for mirrors, prepared by cutting the top and bottom from a blown globe and flattening it on the hearth. These pieces, half or three-quarters of an inch thick, he ordered to be ground in the machine used to polish marble. He then selected the least flawed pieces and had them planed and lightly polished on cast iron plates. Only then did he cut discs and begin to shape the lenses.

Henry Oldenburg's correspondents made frequent references to the want of good glass. Writing to Samuel Hartlib about the Parisian craftsman de Ville-Bressieux's lens-grinding in November of 1659, Oldenburg argued:

> [i]f some pieces of good glass could be sent to him out of England, to work upon (seeing he complaineth of ye difficulty of getting good stuff, and that at Venice they degenerate very much in their art) it would, I believe, oblige him to permit us sometimes to look on his workmanship, which he is very shy to do.[169]

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167 T. Garzoni, *La piazza universale di tutte le professioni del mondo*, Venice, (1585), 129^{r}–130^{v}.
168 R. Smith, *Complete system of optics in four books: A popular, a mathematical, a mechanical and a philosophical treatise*, Cambridge, (1738).
169 Oldenburg to Hartlib, 12 November 1659. **HP Letters** 67/22/9A; Oldenburg 1, letter 169.

In June 1665 the French natural philosopher Adrien Auzout was able to write:

> we have recently acquired at Paris a glassworks where they make the most beautiful glass ever seen, which appears to be wonderfully good for telescopes since the workman makes it without veins and almost without tiny bubbles. For some time there has been another glassworks at Lyons where very good clear glass is made, but I have not yet had time to find out whether this glass, though clear, white and free from bubbles will work better then Venice glass'.[170]

The Paris glass-house was that of the newly established Compagnie Royale des Glaces. Yet by August, Auzout was in some doubt about the French product:

> I know not, whether indeed we shall be so happy, as I promised myself, touching ye goodness of glass, which is made both here and at Lyons for telescopes, and whether we must not content ourselves still with that of Venice (except you have the goodness to send us some plates of yours)[...][171]

The 'points' in this glass were prejudicial in eyeglasses, especially those of microscopes and long telescopes, though less so in objectives.

The Italian-born Tito Livio Burattini, architect, mathematician and astronomer, travelled in Egypt and then was invited to Warsaw. He kept in touch with other astronomers and mathematicians in France and Italy and, through them, with Henry Oldenburg and the English astronomers. In September 1665 Burattini dismissed Auzout's preference for using Venetian mirror, saying that glass cut from large mirrors had been rendered cloudy by the repeated heating process during manufacture. His usual practice was to remelt the glass he used for lenses. He also used 'Ukrainian diamond' noting that in Germany and Italy this is known as Bohemian diamond and presumably referring to natural quartz. This came in pieces of sufficient size for a five-inch lens; it was clear of veins and striations; and it had more body than mountain crystal.[172] Experience proved him wrong, however; for in November that year he wrote,

> I have finished my lens of Bohemian diamond, it is three inches diameter, made one side on a twelve-inch form and on the other a six-inch form, which focusses the rays at four inches. It has taken a fine polish on both sides but after working it I perceived many veins and twists.

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[170] Auzout to Oldenburg, 22 June 1665. **RS** MS A No.5; Oldenburg 2, letter 380.
[171] Auzout to Oldenburg, 12 August 1665. In *Memoires de l'Académie Royale des Sciences de Paris,* vol. **7**, 92–110; Oldenburg 2, letter 393.
[172] Burattini to Bouillau, 24 September 1665. **BN** Bouillau XXVI.

> Testing with another lens I found it gave a good image but overlain with a twisted cloudiness. So I despair of getting anything good and must return to using glass.[173]

News of Burattini's efforts to prepare clear glass reached Auzout and were passed to Oldenburg in February 1666,

> [H]e can[...] make plates of glass, up to 27 or 28 inches in diameter and 1/2 or one inch thick and finding no difficulty to make larger and thicker ones, without veins, and with no more points than Venice glass, of what colour he will.[174]

Burattini had sent lenses of sixteen, twenty and thirty feet focal length, which, in 1670, the astronomer, brewer, city official and instrument maker Johannes Hevelius declared to be 'absolutely outstanding.'[175] Michael Behm, a wealthy Danzig merchant, wrote to Hevelius,

> I wonder that only common lenses (made from sand or from crystals) have hitherto been devoted to telescopes since they demand immense and futile labour, which has hitherto deterred me because of the hardness, little circles [perhaps bubbles], and other things involved of which we have often spoken before this from the letter of Eustachio Divini who rightly complains that thicker lenses (fused from crystal and Venetian glass into certain shapes) often shatter without any external force and are darkened by a certain efflorescent salt of which he himself shows a specimen in the lenses sent to you. Surely there are other transparent materials which could (if they were purified) be shaped into various figures for the sake of experimenting on the extent to which the refractions of the rays vary and occur either at the surface or at the middle of lenses.[176]

In the summer of 1669 Samuel Colepress, a natural philosopher based in Leiden where he worked on the artificial manufacture of opal and recovering the art of making red glass, reported to Oldenburg that 'Benjamin Furlow, owner of a glassworks producing optical quality glass is now at Rotterdam; he charges £5.'[177] Furlow was better known as a merchant and bookseller. Despite Furlow's Rotterdam work, when Huygens wrote to Oldenburg later that year concerned that his own telescopes were inferior because of defects in the material,

[173] Burattini to Bouillau, 12 November 1665. **BN** Bouillau XXVI.
[174] Auzout to Oldenburg, 2 February 1665/6. **RS** A no.9; Oldenburg 3 Letter 488.
[175] Hevelius to Oldenburg, 25 June 1670. **RS** H2 no.21; Oldenburg 6 Letter 1475.
[176] Behm to Hevelius, 5 May 1667. **RS** letterbook II, 67–74; Oldenburg 3 Enclosure 693c.
[177] Colepresse to Oldenburg, 9 July 1669. **RS** Mc C1 no 27; Oldenburg 6 Letter 1223.

Oldenburg responded with the offer: 'we will try to supply you with good material from Lambeth, for there glass is made which is superior to the Venetian, without veins, and very fit for telescopes.'[178] Huygens' reply was immediate:

> If by chance you could send me a sample of Lambeth glass as you kindly offered, I should be very pleased, because since I am unable to find any suitable material here I have ceased work.[179]

The Royal Society now hold three long-focus lenses all inscribed 'C.Huygens' with the focal lengths marked '122', '170,' and 210' and dated '1686.'[180] In 1988 comparison of the abbreviated signature with lenses now at Leiden and Brussels, signed in full by Constantyn Huygens, father of the more famous Christiaan, confirmed that these were also by Constantyn. The lenses are of poor quality glass, having the same refractive index and probably came from the same batch. All are tinged with a greenish-yellowish hue and plentifully sprinkled with bubbles, black specks and striae. Constantyn Huygens used two concave laps to grind the convex faces of the lenses; one lens is plano-convex, with a very accurate plane face. It is unclear why such a poor quality material was thought worth the substantial labour of construction.

The instrument maker and wine merchant Nicolaas Hartsoeker published his *Essay de dioptrique* in Paris in 1694, devoted chapters eight and nine to the working of lenses. The best glass was that for mirrors, containing only sand, soda, magnesium and zaffar (to clear any yellowish tints), and sometimes borax to aid fusion. Nevertheless, he remarked that of more than two hundred large plates of polished glass, he had never found more than two good and five reasonable. The source of these two hundred plates is unknown, but in 1686 Hartsoeker had been sent by royal command to the long-established glass-works at Tourlaville, on the Cotentin peninsula, to procure glass for the telescopes destined for the Paris Observatory.[181] Several of Hartsoeker's comments in his *Essay* appear to be based on his experience of such a glass-works.

Hartsoeker considered that the 'points' which frequently disfigured glass were caused by too-rapid cooling, which allowed a skin to form over the molten

[178] Oldenburg to Huygens, 11 November 1669. **RS** MS O2 no.14; Oldenburg 6 Letter 1319.
[179] Huygens to Oldenburg, 12 January 1669/70. **RS** H1 no.68; Oldenburg 6 Letter 1365.
[180] A. A. Mills and M. L. Jones, 'Three lenses by Constantine Huygens in the possession of the Royal Society of London', *Annals of science,* 46, (1989), 173–182.
[181] 'Année 1686, 7 Juillet, au sieur Guymont, directeur de la manufacture des glaces, pour pareille somme par lui payée pour la subsistence du sieur Hartsucker [*sic*], ingénieur holandais, travaillant par ordre de S.M. à la verrerie de Cherbourg, aux grands verres pour l'observatoire de Paris, 300 livres.' In J. J. Guiffrey (ed.), *Comptes des bâtiments du Roy sous le règne de Louis XIV*, (5 vols., 1881–1901), vol. 2, col.1002.

interior, setting up visible marks of stress. He found that these could be remedied somewhat by reheating the glass, and avoided by allowing a large block of glass to rest within the furnace after the fires had gone out, cooling slowly over several weeks. Another source of trouble came when drops of glass fell from the furnace arch into the pot, while platelets of defective glass within blocks were caused by the glass-workers marvering their molten glass on marble slabs soiled by dust or ash. His advice was to ask the workman for a thick slab of glass which had been rolled not more than twice. Hartsoeker had been paid 300 livres for large lenses for the Paris observatory, and in 1688 he received the balance of 3196 livres 10 s for thirty-three large lenses, a large microscope with three lenses, two burning mirrors and other items, of which twenty lenses went to the observatory and the remainder to Louis Barnabé, a Jesuit going to China.[182]

At his death, Hartsoeker's extensive library and apparatus was auctioned at The Hague.[183] Among the apparatus listed was his burning glass of three feet four inches diameter, the largest then known. There were many burning mirrors; four 'very long' focus glasses; six medium focus objectives with their oculars; eight microscopes and many boxes of microscope lenses; also blocks of Venetian; Niewberg; French; and English glass, the latter described as *rouwe spiegels*, literally 'mourning mirrors', or black mirror glass.

The Italian optical workshops: Divini and Campani

The instrument maker Eustachio Divini of San Severino, Macerata, spent his early years as a soldier before settling at Rome where he studied geometry and astronomy. By 1645 he was in business there as an optical instrument maker.[184] His fine telescope lenses were soon in demand across Europe, though his claims for his instruments and their achievements led him into conflict with Christiaan Huygens over priority of certain astronomical discoveries, and with his fellow optical instrument maker, Giuseppe Campani. In a published letter to his patron astronomer and mathematician Count Carlo Antonio Manzini[185] (of whom more below), Divini reported that he had just completed a telescope of fifty-two feet focal length with four lenses for Cardinal Flavio Chigi, librarian to the Holy

[182] In case the connection with China should appear unusual, it may be noted that the Jesuit J. A. Schall von Bell, who was in China from 1622, wrote his treatise *Juen king cho*, or *De ratione tubi optici*, published in 1669.
[183] *Bibliothèque de feu Mr. Nicolas Hartsoeker ... La vente des livres ... &c.*, The Hague, (1727).
[184] S. Bedini, "A treatise on optics' by Giovanni Christoforo Bolantio', *Annals of science,* 52, (1995), 103–126, 106. Bedini suspects that Divini may have learnt from Torricelli, though documentary evidence is acking.
[185] E. Divini, *Lettera ... all'illustrissimo Signore Conte Carl'Antonio Manzini in cui si ragguaglia di un nuovo lavoro e componimento di lente, che servono a occhialoni, o semplice o composti*. Rome, (1663).

Roman Church since 1659. Its manufacture had taken over a year because it was hard to find flawless glass of sufficient size. Eventually he ordered twenty-four pieces from Venice and had them polished like mirrors, in order to show up any defects. Having worked the three that seemed clear, he discovered that they were veined with fine straight lines. He attributed this defect to the way that the glass-maker pulled the molten glass from the furnace, twisting it on the iron, and returning it to the furnace. In particular the Venice glass known as *gettati* or *gocciale* (probably cast) was the most effected, as it did not 'obey' the metal former, probably because of internal stress resulting from the casting. Another Venetian glass, found at the Frezza glass-house in Rome, was the least discoloured and resembled rock crystal, but had the defect of 'weeping'. Lenses made from it had to be dried before each use. The common spectacle-makers agreed that it was difficult to polish because of its softness. Huygens echoed the complaint that certain glasses sweated or wept. This sounds rather like the low-lead glass that caused glass-maker George Ravenscroft so much trouble in his early trials (see Chapter Two). Divini was reported to also use old mirror glass, perhaps for the smaller lenses.[186]

Giuseppe Campani rose to fame in the 1660s as the supreme craftsman whose microscopes and telescopes were sought after by astronomers and wealthy virtuosi all over Europe. Originally from Spoleto, Campani and his brothers arrived in Rome around 1650. His brother Matteo was a priest, with strong scientific interests, another, Pietro Tommaso, was a clockmaker, and it is thought that Giuseppe may have been able to study optical sciences at the Collegio Romano.[187] At first, Campani was friendly with Divini, whose reputation as an optical instrument maker was already established, but a dispute over the priority for a particular feature on a clock made by Giuseppe and Matteo Campani led to a rift which widened over the years that Giuseppe Campani and Divini were in direct competition.[188] Campani became secretive about the techniques that were bringing custom from near and far, and he refused to admit anyone to his workshop. He laboured alone except for his one surviving daughter, whom he trained, reputedly to his own level of skill. In 1664 he published, in the form of a letter, *Ragguaglio di due nuove osservazioni una celeste in ordine alla stella di Saturno: e terrestre l'altra in ordine agli strumenti medesimi, co' quali si e fatta l'una e l'altra osservazione, dato al Serenissimo Principe Mattia di Toscana*. Here, he described several telescopes of extremely long focal length and his use of them to observe Saturn. Acknowledging the previous work of astronomers Francesco Fontana and Anton

[186] Beale to Hartlib, 10 February 1660. **HP Letters** 67/22/8A.
[187] S. Bedini, 'The optical workshop equipment of Giuseppe Campani', *Journal of the history of medicine*, 16, (1961), 18–38.
[188] S. Bedini, 'Giuseppe Campani, pioneer optical inventor', *Proceedings of the Xth International Congress of the History of Science, Ithaca 1962,* 1, (1964), 401–404.

Maria Schyrleus de Rheita, he disclosed, though without giving details, that he had invented a certain type of lathe for grinding and polishing lenses. With this lathe, lens blanks cut from glass sheets could be ground directly without being first cast in moulds.

The Campani workshop equipment

Campani died at the advanced age of eighty. It is unclear whether his daughter continued production, but Campani's equipment was certainly preserved. In 1746, however, she sold the entire collection to Prospero Lorenzo Lambertini, Pope Benedict XIV, who intended to present it to the Institute of Sciences in Bologna, his native city.[189] Ercole Lelli, a craftsman from Bologna who had some knowledge of optics and had already made lenses, was ordered to go to Rome and to demonstrate his capability by producing lenses with Campani's apparatus. In 1747 the apparatus was inventoried and transferred to Bologna. Lelli conversed with Campani's daughter and produced the inventory. In 1768, a century after Campani flourished, French academician, Augustus Denis Fougeroux de Bondaroy, published an examination and discussion of the episode. Despite the chronological gap, Fougeroux de Bondaroy's account is informative on seventeenth-century practice.[190] In the years following the inventory and transfer of Campani's apparatus it disappeared. However, sufficient remains at Bologna,[191] together with several lenses, to provide a feel for the nature and quality of the tools which would have been in daily use by Campani and his fellow craftsmen.

The inventory runs to nineteen pages. Summarized, it describes eighty-six metal forms to work convex crystal with emery and tripoli, two of each size—one for grinding and one for polishing, dimensions ranging from 200 palms[192] (that is, for lenses of approximately 132 feet focal length) to 1 inch, including ten tiny forms for 'crystal pearls' for microscope lenses; thirty-one forms for grinding convex crystal with sand, one of each, ranging down from eleven palms six inches, and another fifteen, not in the previous sequence; thirteen brass forms for concave glasses; thirteen ditto of tin; fifteen hemispheres for finishing concave glasses and fifteen for making crystal fillets. Brass handles ranged in size from those

[189] G. Dragoni, 'Il patrimonio storico scientifico del Museum di Fisica attraverso li secoli: Dal seicento ai nostri giorni', in G. Dragoni (ed.), *Instrumenta: Il patrimonio storico scientifico Italiano. Un realtà straordinaria*, Bologna: Grafis, (1991), 73–86.

[190] 'Inventari delle camere di ottica e diottica'. Bologna: Archivo di Stato, Assunteria d'Istituto, Diversorum busta 10, No. 15. (A 19-page copy of the inventory dated 28 September 1747); A. D. Fougeroux de Bondaroy, 'Memoire sur la manière de travailler les objectifs employés par Campani', *Memoires de l'Académie Royale des Sciences de Paris* [for 1764], (1768), Histoire, 169–175; Mémoires, 251–261.

[191] In the Department of Physics, University of Bologna.

[192] 1 Roman palm = 8.79 inches.

suited to hold glasses of 200 palms downwards—there were up to six of each size, 132 in all; there were four handles for spectacles and twelve for theatre glasses, and eighteen tiny handles with small globular feet. There were forty-six little plates for handling concave glasses and twenty-six for removing the film that results from polishing with emery. There were numerous measures, made of stiff or flexible brass, and serving to gauge each part, for a full range of telescopes and microscopes, at every stage of production. Everything seems to have been delivered, as it had been found in Campani's workshop, including sundry tools, files, skins, a supply of special paper to paste down on the formers when polishing, frames, stands, and several lathes of various types and sizes. Boxes of spectacle, microscope and telescope lenses are listed, plus 184 unground lenses. None of this equipment was out of the ordinary, and Fougeroux was left to conclude that Campani's achievement derived from his frequent changing of formers to maintain accuracy, and his extreme care, and that his reputation had been enhanced by his refusal to allow any lens that he considered less than perfect to leave his workshop.

Non-professional lens-makers

Eminent among the non-professional makers of telescopes and microscopes in Italy was Manfredo Settala,[193] known as 'the Milanese Archimedes.' The Würzburg teacher of physics and mathematics; author of *Magia universalis*, *Physica curiosa* and, *Technica curiosa*; Gaspar Schott praised Settala as the best of the present craftsmen.[194] Settala studied law at Pavia, Siena and Pisa, before developing an enthusiasm for the natural and exact sciences. He travelled widely in Italy and through the eastern Mediterranean, and spoke Spanish, French, Armenian and English. He was said to belong to many learned societies; not, however, to the Royal Society, as was claimed, though he did correspond briefly with Oldenburg. Skilled at mechanics, he worked at the lathe and made his own watches and precision instruments, notably microscopes and burning glasses. The catalogue of his museum, a varied assemblage typical of the day, indicates that he had two telescopes of around eighteen feet, four of around twelve feet, and 'many' of ten feet or less, equipped with four lenses of especially good quality, besides other lesser telescopes and microscopes.[195]

The scholar of European studies, Deac Rossell, makes the point that the London lens-grinding trade was far more professional than in German towns such as

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[193] Artical 'Settala' in J. F. Michaud, *Biographie universelle, ancienne et modern*, Paris, (45 vols., 1843–65), vol. 39, 176.
[194] Schott, in his *Magia universalis* of 1657 rated Settala best, followed by Divini and Wiesel; Maignan, Toricelli and Fontana were in his second rank.
[195] [P. F. Scarabelli], *Museo o galeria ... dal Signor Canonico Manfredo Settala nobile Milanese,* Tortona, (1666).

Nuremberg.[196] Rossell identifies a distinct social difference between continental and London lens-makers, probably based on the larger size of the London professional trade. In Enlightenment Germany lens-making was the work of amateurs, who then passed on their work to acknowledged professionals for sale. Lens-making was seen as a respectable leisure occupation which gave its practitioners access to other intellectuals and the local scientific society. It could also provide an income to an educated but perhaps not well-paid family. In terms of the hours spent, it was a repetitive, dull and somewhat unrewarding task which professionally competent craftsman undertook only for special orders. Not every workshop kept the machinery or the young labourers to turn out all the lenses that might be called for.

This domestic lens-grinding was practiced by the philosopher Baruch Spinoza when his rift with Amsterdam's Sephardi Jewish community obliged him to leave the merchant business he had previously run with his brother. By 1661, when he settled in the village of Rijnsburg, near Amsterdam, he had some skill and reputation, not just for his lenses but also for his telescopes and microscopes. Lens-grinding provided Spinoza with the modest income which satisfied his needs, while the tedium of the work gave him time for serious thought. This work on lenses was part of his general scientific interest, including a study of optics. It had been stimulated by his reading of Descartes, and was sustained by his personal acquaintance with Christiaan Huygens and Henry Oldenburg, with whom he kept up a lifetime correspondence, ranging across their common interests in matters of science and religion. Huygens and the philosopher Gottfried Willhelm Leibniz both praised the quality of his microscope lenses. In his biography of Spinoza, Steven Nadler makes the valid point that the glass dust generated by domestic lens-grinding may have exacerbated the respiratory problems leading to Spinoza's early death.[197]

Deac Rossell identifies several prolific makers of lenses who participated in the networks of correspondence and also wrote books, while pursuing other full-time occupations.[198] Among these he names Johann Georg Leutmann, a protestant pastor in Dabrun who made lenses and wrote *Neue Anmerckungen vom glaß-schlieffen …* , published in 1719. Here, Leutmann claimed that he had better machinery than Christian Gottlieb Hertel, the author of the now more famous *Vollständige anweisung zum glaß-schlieffen* published three years earlier. Johann Conrad Beuther, engineer and author of several books on coins, taught mathematics at the Augsburg St Anna-Gymnasium from 1772 to 1778. The

[196] Deac Rossell, private correspondence, 2003.
[197] S. Nadler, *Spinoza: A life*, Cambridge: Cambridge University Press, (1999), 182–4; M. B. Hall, *Henry Oldenburg: Shaping the Royal Society*, Oxford: Oxford University Press, (2002), 61–3.
[198] Deac Rossell, personal correspondence, 31 October 2003.

sculptor and model-maker Daniel Volkert, from Danzig, was noted for his *anamorphosen*; that is monstrous, distorted perspectives; but also made lenses as a sideline, which he sold on to others.

The man whom Rossell sees as central to the German correspondence network is Johann Franz Griendel von Ach, a Capuchin monk who in 1670 converted to Lutheran protestantism and moved to Nuremberg. Famous for his microscopes, the last page of his *Micrographia nova* bears a recommendation to Johannes Zahn's *Oculus artificialis teledioptricus sive telescopium* of 1685. In turn, Zahn describes Griendel's microscope and identifies the Lutheran convert as his 'former teacher of teledioptrics'. Since Zahn was a Premonstrate canon in Würzburg, their friendship must have begun when Griendel was a Capuchin in the same town, and continued despite the change of confession. Zahn was also a professor at Würzburg. His book deals principally with the human eye and its defects and remedies by spectacles. Volume III, `Practico-mechanicum', illustrates by crude woodcuts the basic apparatus for preparing abrasives and working lenses. Fine engravings depict Emanuel Maignan's machines for cutting metal concaves. Maignan himself was a Minim, living in Rome. His *Perspectiva horaria, sive de horographica gnomonica tum theoretica tum practica,* Rome, (1648), was a comprehensive study of sundials, to which are added descriptions and copious illustrations of three 'novel' lathes.

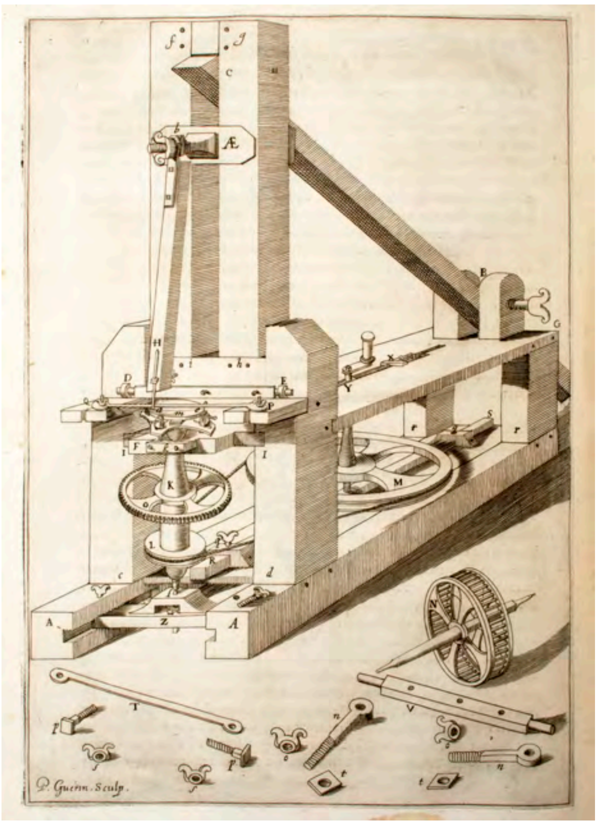

Figure 28: Maignan's concave form lathe. Designed by Maignan the figure shows a vertical lathe for cutting spherical forms. This was a version of a tool actually used by lens craftsmen to accurately shape the concave forming pans in which convex lenses were ground. [199] Emanuel Maignan, *Perspectiva horaria*, Rome, 1648, 688. © Whipple Library, Cambridge, STORE 69:8.

[199] D. G. Burnett, *Descartes and the hyperbolic quest: Lens making machines and their significance in the seventeenth century*, Philadelphia: American Philosophical Society, (2005), 79–80.

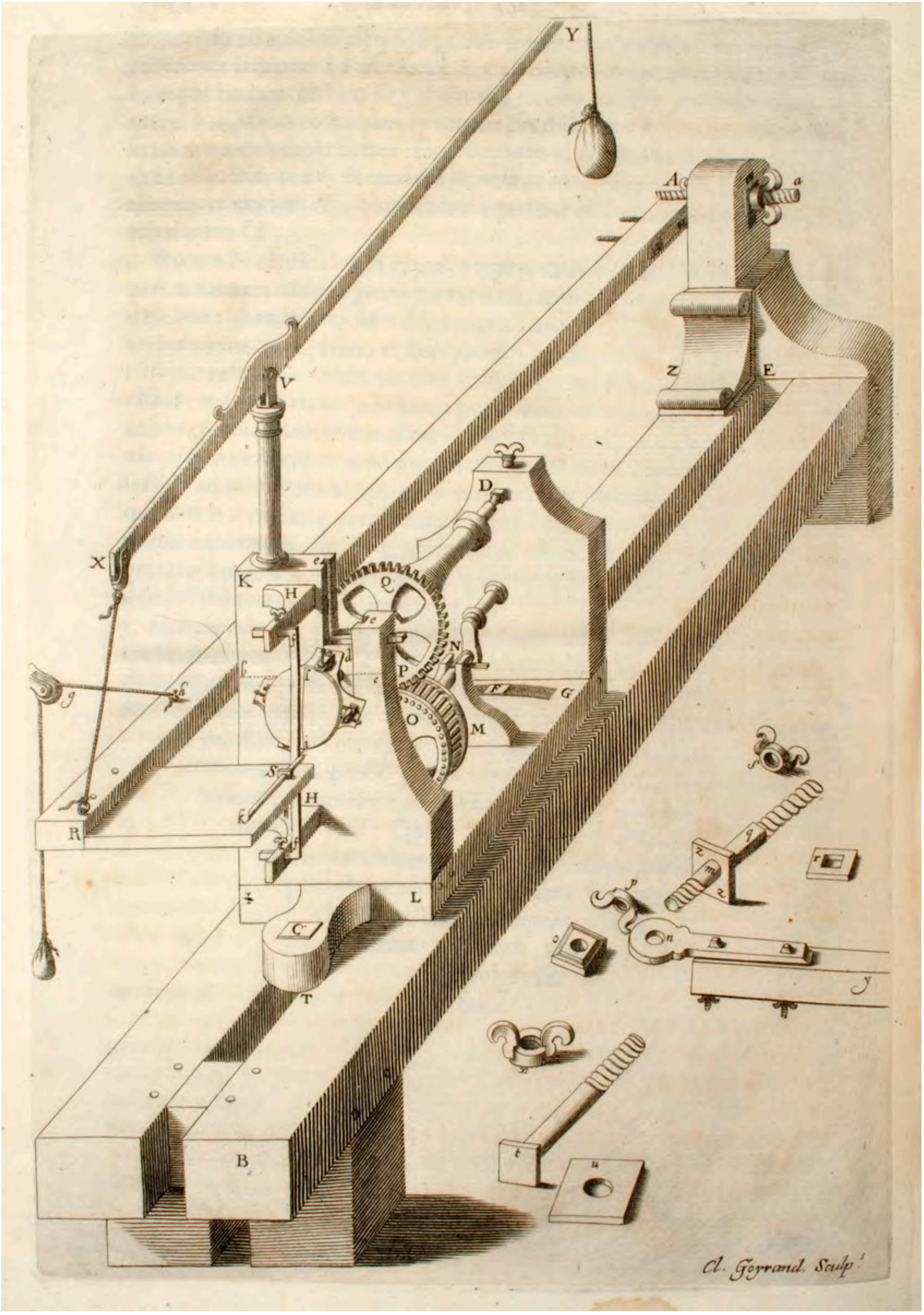

Figure 29: Maignan's convex form lathe. As with figure 28, this instrument was designed by Maignan and represents a more complex version of the same kind of lathe, constructed to produce convex forming plates that could be used to grind concave lenses.[200] Emanuel Maignan, *Perspectiva horaria*, Rome, 1648, 691. © Whipple Library, Cambridge, STORE 69:8.

[200] *Ibid.*, 80.

Optical theories

The simple telescope with its convex objective and concave eyepiece, modified by the astronomer Johannes Kepler, was soon endowed with three, four, or even more lenses. Such multiplications enhanced the optical dexterity of the instrument, but the gain did not necessarily outweigh the vision lost with the increased thickness of glass. Most of the many seventeenth-century books dealing with optics carry diagrams of the ray paths for such multi-lens telescopes. One author to whom nearly all later writers pay homage in this respect is the Milanese Jesuit Girolamo Sirtori better known by his Latin name, Hieronymus Sirturus, whose *Telescopium, sive ars perficiendi novum illud Galilei visorium instrumentum ad sydera, in tres partes divisa* was published at Frankfort in 1618; the other is the astronomer priest Johann Burchard, better known by his name in religion and his birthplace of Reutte in the Tyrol, as Anton Maria Schyrlaeus de Rheita. His *Oculus Enoch et Eliae* was published at Antwerp in 1645.[201]

Rheita joined the Capuchins and studied at Ingolstadt, before moving to Passau and then to Linz. He travelled widely over Germany, France, Italy and Austria, always seeking to improve the construction of telescopes. He described the astronomical telescope and its advantages, with the use of the third erector lens, and a fourth convex 'field lens' in the compound eyepiece to enlarge the image. Rheita's book is unusual in that it recommends a craftsman, in this case Johann Wiesel of Augsburg, whom Rheita claimed to have instructed as to theory. He also illustrated binocular telescopes, hence the title of his book, the two lines of sight through the binocular echoing the biblical tradition that Enoch and Elias went together directly into heaven.

The type of each lens— plano-convex and plano-concave, or double convex and concave—and their number and arrangement within the telescope or microscope tube were discussed at length, with figures given in virtually all optical texts, since Kepler's *Dioptrice* of 1611. The figure of the lens must be calculated with regard to the refractive index of the glass. Mathematicians John Pell and Charles Cavendish had appreciated the need to do this; it is however seldom mentioned in treatises on lens-making. The authors may have been unaware of the variability in different batches of glass, or simply discounted it. Descartes, with his mathematical rigour, illustrated a simple wooden frame to hold a prism of the glass under test. A ray of light was directed through a pinhole on the frame, and passing through the prism, fell across a rule, graduated to show the angle of refraction. Descartes had experimented with prisms of rock crystal, Venetian crystal and common glass, finding that the natural mineral had the

[201] R. Willach, 'Schryl de Rheita und die verbesserung des linsenfernrohres mitte der 17. jahrhunderts', *Sterne und weltraum*, 2, (1995), 102–110; 3, 186–192.

highest, and common glass the lowest angle of refraction.

Publications on machine tools for shaping the basins and formers

Figure 30: Portrait of Emmanuel Maignan, engraving by Nicolas Bazin after a painting by Joannes Michel. Wikimedia Commons, CC-PD-Mark.

Once the curve for the lens had been calculated, it was drawn, and copied in thin sheet brass to serve as a template for the metal basins or formers. These basins were cast in any one of several metals, according to preference, but the precision and the absolute smoothness of their surfaces was crucial to the finished product. The grinding process was the most tedious part of the operation, and although it could be done entirely by hand, various devices were adopted, to allow unskilled hands to perform the labour or simply to reduce the hours of toil. After Sirtori's *Telescopium* of 1618, which may have already become somewhat rare, the basic tools for hand-grinding were illustrated by Zahn in his *Oculus artificialis teledioptricus* of 1685, a book which many later authors referred to as one of their sources.[202] The simplest device was that mentioned by Beeckman and shown in various illustrations, where the lens was held on a block suspended on a rod equal in length to the radius of the desired curve. The workman swung the block in a series of circular motions, to achieve a smooth convex surface to the lens. Christiaan Huygens sketched a modified version in about 1660, where the rod itself hung from a counterbalanced beam.[203] Rheita mentioned the use of turned basins to shape convex lenses; described a machine for hyperbolic lenses; and explained 'a new way' of turning spherical basins on the lathe, which Beeckman had in fact described earlier. The first lathe described by Maignan in his *Perspectiva Horaria* of 1648 seems to be an attempt to mechanise the suspended-rod device. In 1646 Maignan had been eagerly awaiting a sight of Rheita's book, and presumably made use of it when composing his own text.

Lathes, or turn-benches as they were sometimes called, were coming into use by the late fifteenth century, and were illustrated in sixteenth-century books of

[202] J. Zahn, *Oculus artificialis teledioptricus*, Würzburg, (3 vols., 1685).
[203] C. Huygens, *Toutes les oeuvres et la correspondence de Christiaan Huygens*, 17, (1932), Fig.21, 299.

machines. They could be found both in aristocratic houses and the humbler workshops, being employed by the nobility for decorative turning of ivory and other rare materials and by craftsmen to make components for everyday products. Originally for shaping wood, they had been adopted by artisans working hard decorative stones, and adapted for screw-cutting, but were seldom described in connection with glass-grinding. Della Porta did not mention them; Sirtori however advised those of his readers who did not have access to a craftsman who could polish their concaves to purchase a lathe. Most of the machines described and illustrated are intended to shape the metal basins or formers. Various arrangements of the axis, the workpiece and tool, and the driving force are possible. The axis or spindle may be vertical or horizontal; either the workpiece, that is, the basin, or the tool, that is, the steel cutter, may turn; and the motion may be either back and forth, if driven by a bow; or rotary, if driven by a cranked handle or treadle, via a pulley. Although on most lathes the glass disc was held against the basin, for large lenses the hand pressure could not be applied equally throughout. Machines for large convex spherical lenses, and that of Descartes, turned the glass mechanically and were made from 1662 by Huygens; Hooke, perhaps having learnt from Drebbel's son in law; and by Campani.

Maignan illustrated what he claimed as new forms of lathe, showing general arrangement drawings and details of certain individual parts. There were two lathes for turning spherical concave basins, and one for turning hyperbolic concave and convex basins, and the tools for shaping them. The first lathe, mentioned above, had a vertical spindle, rotary drive to the workpiece, and hand-moved tool. The second had a horizontal spindle, geared rotary drive to the workpiece, and hand-moved tool. The mode of operation of the third, where a complex movement of the tool is required in order to generate hyperbolic basins, is unclear. The engraver may have been working from a sketch, rather than from the apparatus itself.

The Bolognese nobleman Carlo Antonio Manzini in his *L'occhiale all'occhio* of 1660 gives a practical guide to the processes of lens grinding. For Manzini, some of the turn-benches and lathes described in print were triumphs of design over practicality, the inventor having allowed the laws of physics to override the laws of mechanics. He depicts a vertical-axis lathe, where the workman is seated, his right hand cranking the pulley wheel that rotates the basin, his left hand pressing the glass disc against it. The workman's posture looks very uncomfortable and the grinding action is taking place above his head, so that it is difficult to imagine that he could perform well in this situation. Two bench lathes which brought the workpiece into a more comfortable position were also illustrated by Manzini, one being that developed by Ippolito Francini, one of Galileo's lens-grinder, where the spindles of both pulley and former were horizontal. It is not clear if this lathe required one or two operators, but here too it appears that the workman would be forced into an uncomfortable posture while grinding. Manzini improved Maignan's lathe of 1648, turning it on its side so that the spindle was horizontal. The illustration appears rather more practical than the earlier device. The glass blank was attached to the end of a rod supported on a rest, thus keeping it centred on the basin. Huygens sketched a similar device around 1665.[204]

Johannes Hevelius at Danzig was unaware that anyone before him had shaped convex lenses on the lathe. He proposed in 1647 to work several small lenses simultaneously by means of a vertical treadle-operated lathe with a wooden pattern fitted to the mandrel. The lens blanks were fastened with pitch to the wooden pattern and the metal grinding tool was pressed down onto them as the pattern revolved, until the blanks were ground to the figure of the tool.

Michel Lasérré, a Capuchin friar who took the name in religion of Chérubin d'Orléans, dedicated his 'little treatise' to the comptroller-general of finances under French King, Louis XIV of the House of Bourbon, Jean-Baptiste Colbert. The diminutive was something of a misnomer for a handsome volume of over four hundred pages in-folio, lavishly illustrated with fine engravings cut from Chérubin's own drawings.[205] He claims that there is nothing shown in the machines that he has not tried and used, and that all their components are already known in the mechanical arts To judge from the number of times it is mentioned by later writers, Chérubin's *La dioptrique oculaire* of 1671 enjoyed an extremely wide readership, less so his second book, *La dioptrique parfait,* published six years later, in which he described the construction of his binocular telescope. He argued that one of his profession could not afford to buy long telescopes, which had led him to study the art and to make telescopes for himself and his friends. Chérubin recognized the defects of the complicated machines that had been proposed by theoreticians such as Descartes and his followers. He sought rather to design a simpler machine to be guided and corrected by the hand of a competent craftsman. Such men he distinguished from the uneducated artisans who were both ignorant of the finer points of their crafts and untidy and careless in their methods.

La dioptrique oculaire takes the reader through three stages. The first is the shaping of the basins and lenses entirely by hand and simple lathe, using the earlier traditional methods. For the basin metals he prefers iron or brass, soft enough to be workable yet retaining their shape. Pure tin, which Chérubin

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[204] C. Huygens, *Toutes les oeuvres et la correspondence de Christiaan Huygens*, 17, (1932), Fig.24, 301.

[205] Chérubin's practices are comprehensively described and illustrated in D. G. Burnett, *Descartes and the hyperbolic quest: Lens making machines and their significance in the seventeenth century*, Philadelphia: American Philosophical Society, (2005), 107–121.

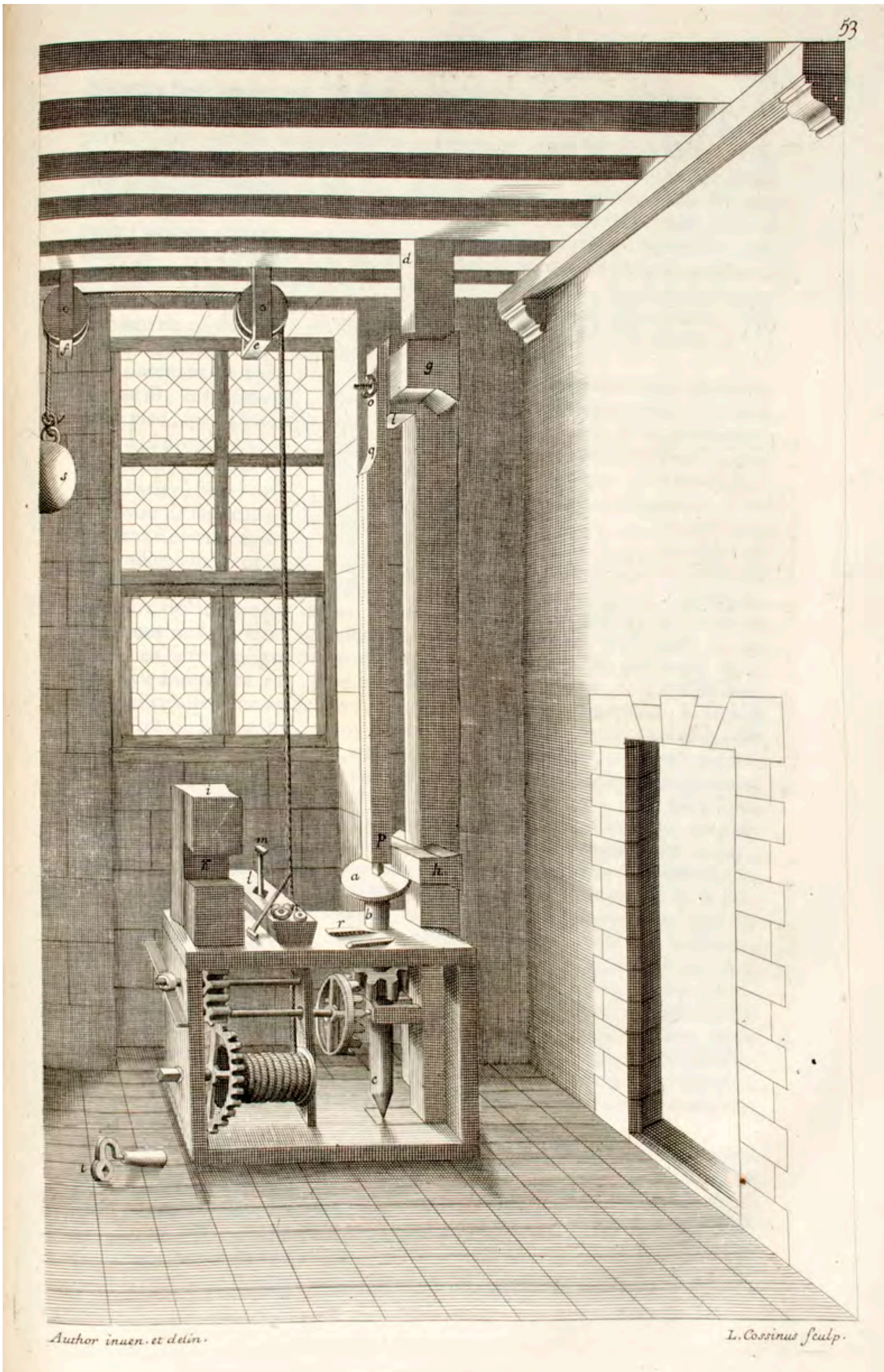

Figure 31: D'Orleans' weight-driven apparatus for mechanising the rotating tool for shaping metal basins. The winding handle is shown on the floor to the left.[206] Chérubin d'Orleans, *La dioptriqve ocvlaire*, Paris, 1671, plate 53. © Whipple Library, Cambridge, STORE 69:4.

[206] *Ibid.*, 116.

prefers sourced from England than Spain, is acceptable for rough working but bell-metal is no good.[207] The second stage consisted in working basins and lenses with a hand guided by simple machines, including suspended polishing stones and upright grinding machines (see above). In the third stage the hand was directed by the machine, which has become more complex, with a range of motions controlled by pivots, set screws and worm gears (see below). The cutting tool was directed to shape the basins, or in one case, the glass itself.

Chérubin is known to have employed two of the leading Paris opticians, Daniel Chorez and Guillaume Ménard, who made telescopes for members of the Académie Royale and the Paris observatory; it is possible that they made the metal basins for him to polish his own lenses.

A small anonymous booklet, *Kurze anweisung die gläser zu schliessen*, published at Dresden in 1680, gives a brief account of how to cut the metal guides for hyperbolic and elliptical curves, prior to polishing lenses, for which its author recommends Venetian glass. Zahn's *Oculus artificialis teledioptricus* of 1685, has some crude woodcuts of basic apparatus, also a very fine set of engravings depicting Maignan's concave-forming machine and its parts. Other illustrations show the construction of telescopes and microscopes, and how to make prisms and various polyhedra.

Hartsoeker disliked machines, preferring to prepare his lenses entirely by hand; two of those hands belonging to his wife, Elisabeth Vettekeucken. He made his formers from glass, testing their curvature by reference to lenses of known focal length. The formers were shaped by grinding with sand and emery, and then lined with smooth paper. The lens was polished with tripoli. Hartsoeker claimed that there was no better method for preparing spherical lenses, and as for non-spherical, they were less accurate than theorists might wish. He allowed that oculars might be worked on metal, these being less subject to change of shape than glass forms. Machines were however essential for tiny lenses, which could not easily be manipulated; they could be polished very effectively in papier-mâché or wooden formers. For the smallest sizes, drops of glass held on a needlepoint and melted in a flame could be formed into globules that needed no further polishing.

[207] C. d'Orléans, *La dioptrique oculaire*, Paris, (1671), 339.

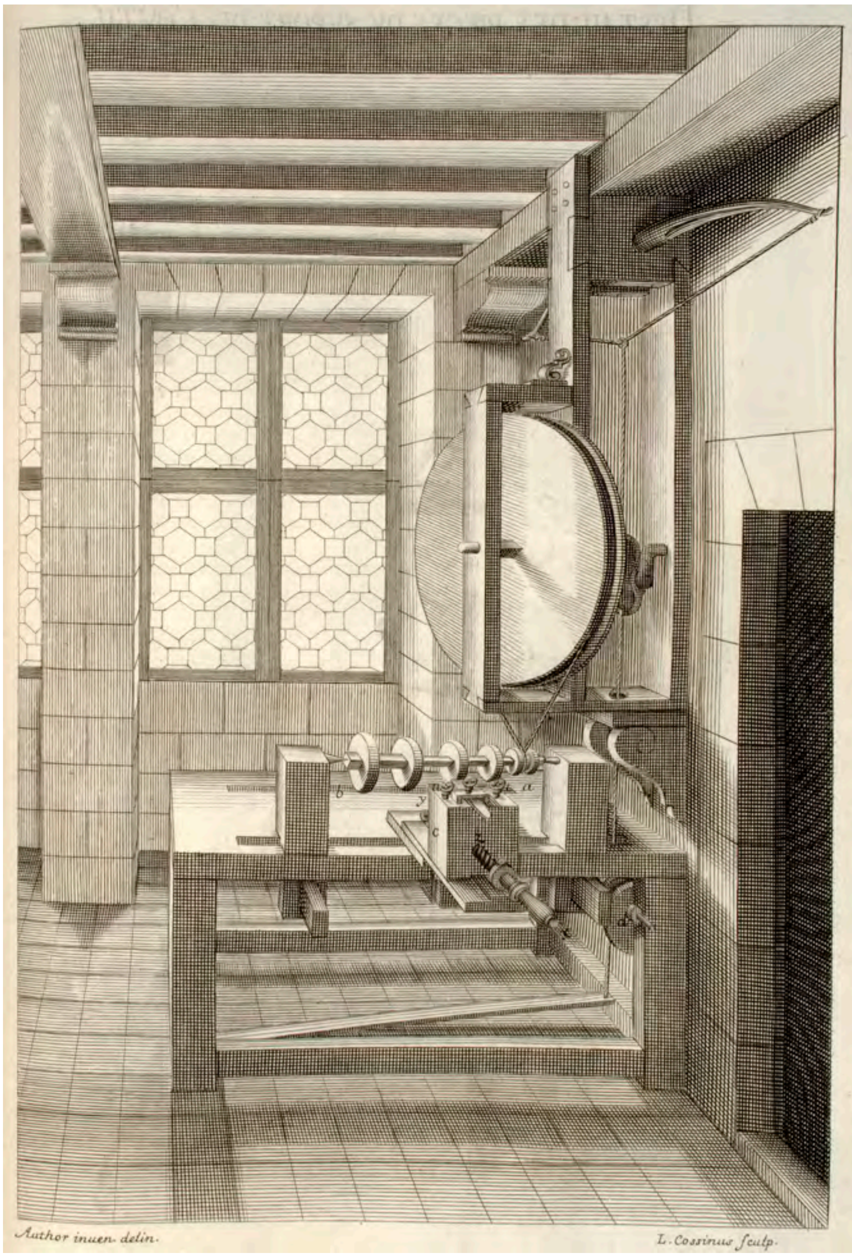

Figure 32: D'Orleans's illustration of a treadle-operated turret lathe, a rotating tool to grind metal basins and for working small ocular lenses. The operator can select from a range of tools of varying circumferences, according to the desired curvature. The striking characteristic of this design is the development of an articulated "turret" for holding the cutting tool, or in some cases the work itself. These complex devices have a range of motions (by mean of pivot, set screws and worm gears), and enable the work of cutting a form (or positioning the work against a form) to be carried out by means of the manipulation of an established set of mechanical parameters. In this sense, these systems represent some of the very earliest precision grinding systems, where the work is controlled by a fully articulated rest.[208] Chérubin d'Orleans, *La dioptriqve ocvlaire*, Paris, 1671, plate 56. © Whipple Library, Cambridge, STORE 69:4.

[208] D. G. Burnett, *Descartes and the hyperbolic quest: Lens making machines and their significance in the seventeenth century*, Philadelphia: American Philosophical Society, (2005), 116.

Descartes and the hyperbolic lens

The convex or concave lenses mentioned above were, with a few exceptions, shaped to spherical curves. For a brief period, strenuous attempts were made to grind non-spherical basins for shaping lenses, in the hope of reducing aberration. The mathematician and natural philosopher, Réné Descartes, was the name most commonly associated with such attempts.[209]

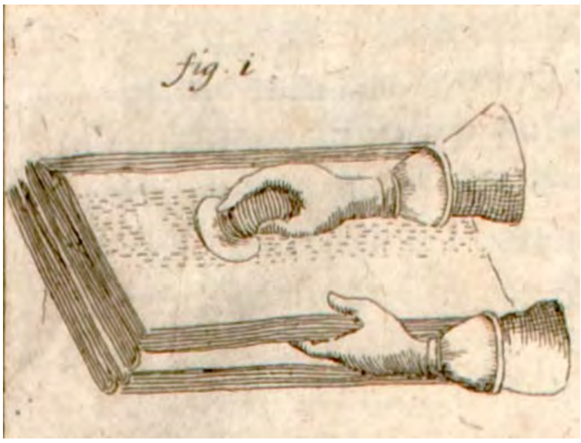

Figure 33: The diagram shows an example of manual grinding on a planar surface to produce a hyperbolic lens. The grinding for a hyperbola followed straight sweeps rather than circular motion. The lens is held by the mollette (see Figure 26). Johann Zahn, *Oculus artificialis teledioptricus*, Herbipoli: Sumptibus Quirini Heyl, 1685–6, 'Fundamentum III', 'Practico-Mechanicum Fabrica', 34, iconismus VI, fig. 1. © Whipple Library, Cambridge, STORE 43:17.

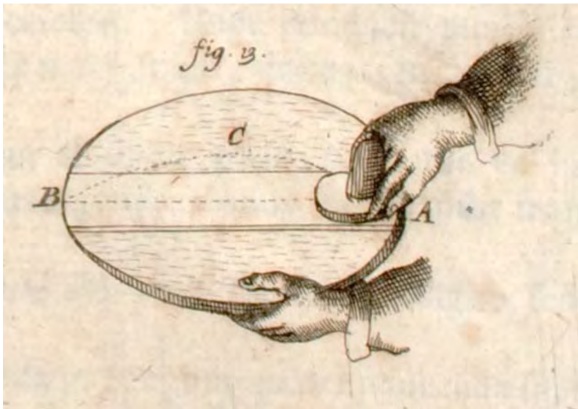

Figure 34: In this diagram the illustrator attempts to show how straight sweeps of the grinding surface could shape the lens blank to a hyperbola. The lens is held by the mollette (see Figure 26). Johann Zahn, *Oculus artificialis teledioptricus*, Herbipoli: Sumptibus Quirini Heyl, 1685–6, 'Fundamentum III', 'Practico-Mechanicum Fabrica', 34, iconismus VI, fig. 13. © Whipple Library, Cambridge, STORE 43:17.

Descartes had studied with the Jesuits in Paris before spending nine years on military service outside France. He returned to Paris in 1623 with a reputation as a military engineer and man of learning, which brought him into the company of like-minded savants in that city. In Paris he renewed his acquaintance with Mersenne and the mathematician Claude Mydorge. It is unclear where Descartes learnt his method of finding the curve for a lens. He denied borrowing his elliptical and hyperbolical lens theories from Kepler while admitting that Kepler had been his first teacher of optics and that a diagram in Kepler's *Dioptrice* of 1611 may have inspired him. His method was disclosed to Beeckman in October 1628 but was kept from Mersenne until 1632.

Although familiar with the range of machines in use and illustrated in books,

209 *Ibid.* gives a detailed and well-illustrated account of this episode.

Descartes was not a mechanic and to put his ideas into practice he recruited several craftsmen from the instrument-making community. The first associate was a young mathematical instrument maker named Jean Ferrier[210] who had made instruments for the mathematician Jacques Aleaume.[211] When Aleaune's books and instruments were sold at his death, some of the instruments probably went to Mydorge, who employed Ferrier, as did the mathematician and astronomer Jean-Baptiste Morin. Oldenburg, visiting Paris, met the optician Etienne de Ville-Bressieux, who was also said to be working for Descartes; de Ville-Bressieux asked Oldenburg to procure some good glass for him as this was generally unavailable in Paris.[212]

Ferrier claimed to be able with great care to turn a hyperbolic convex lens, but he was unable to turn a hyperbolic concave due to the speed of the lathe being greater at the rim of the glass than at the centre and therefore cutting more glass from the rim. He and Descartes worked closely together up to 1629, though their actual progress is not recorded. Historian D. Graham Burnett explains that Descartes' intention was to create lenses based on optical principles, rather than by the vagaries of the craftsman's hand. He also wished to prepare aspherical lenses of hyperbolic or parabolic section, to reduce the colour fringes and blurring found on images seen through spherical lenses. The plan was that Descartes would design, and Ferrier would construct, lathe-based machines which when set up would cut basins for grinding such aspherical lenses. The craftsman would merely provide the rotative power and have no part in shaping the tool.

In June 1629, when Descartes was back in the Low Countries, he wrote inviting Ferrier to Franeker as he had now devised a method to grind elliptical lenses. But the young man, now building a reputation among the Parisian savants, was probably getting more commissions from that source and he declined to move. In October, Descartes moved to Amsterdam He disclosed to Ferrier than his idea was to adapt a lathe which had previously been tried in Paris without success, by rigging a guide which enabled the lathe to cut a curved blade which was used to shape a soft grind-stone, and this finally cut the lens. He considered it essential that the lens and the grind-stone should turn at different speeds. His intention at this stage was not to make microscope lenses, which were ground on both faces, but to achieve a plano-convex and a plano-

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[210] *Ibid.*, 1, n.1. Burnett explains that there were probably three Ferrier brothers, Antoine, Guillaume and Jean. Earlier writers had disagreed as to which had worked for Decartes, but a letter of 1634 from J-B. Morin found among Mersenne's *Correspondence* (vol. 1, 516) confirmed the first name as 'Johannes'.

[211] A very informative article on Jacques Aleaume can be found on French Wikipedia: https://fr.wikipedia.org/wiki/Jacques_Aleaume [accessed August 2016].

[212] **Oldenburg.** vol. 1, 270, 327, 329.

concave lens for a telescope, believing that lenses of excellent quality would reveal sufficient detail to confirm life on the moon.

Ferrier recognized several impracticalities in Descartes' plan, namely, the geometric arrangement which was intended to guide the lathe was faulty, that a second blade would be required to shape the convex side of the lens, that the blade would dull on cutting the stone, and that abrasive would soon wear the stone. He proposed several masterly improvements, replacing the grindstone and its axle with one piece of brass or iron, and positioning it above the lens to reduce the loss of abrasive, and pouring an oil-water emulsion on the stone to make the abrasive adhere. He recommended avoiding the use of cogs and wheels in the lathe drive, as these always meshed unevenly and caused small dents or bumps to form, and he recommended rough-shaping the lens before applying it to the stone.

In January 1630 Descartes heard that Ferrier was now planning to join him in Amsterdam. The news threw him into a panic, which manifested itself as hostility to Ferrier, whose skill and behaviour he then criticized in letters to his friends. Ferrier persevered even so, and in Paris his skill was appreciated. He obtained an apartment in the Louvre, an honour bestowed on fashionable artisans. He showed a microscope and made telescopic sights for quadrants. At last Descartes wrote to congratulate him and remarked that Constantyn Huygens had constructed a lathe to his design but had experienced considerable difficulties in getting results. This admission shows that, however brilliant the theory, it required the collaboration of a skilled craftsman to put it into effect. Meanwhile, Descartes’ efforts were not kept rigorously secret and his endeavours were closely followed in Paris and beyond.

When others tried to put Descartes’s mathematical statements into practice, they found, as Manzini had vividly described it, that the laws of mechanics overwhelmed those of physics. Constantyn Huygens senior, who may have learnt the art of lens grinding from Drebbel, wrote to Descartes in 1635 that he was employing an optician at Amsterdam to make a hyperbolic lens. The endeavor did not gone well, for in June 1636 Descartes sent him a model of a hyperbolic curve; the following month Huygens sent Descartes a lens, only to have this second attempt rejected by Descartes. In October 1637 wrote that the lenses were still unacceptable; that the machinery was easy to make; the polishing should not destroy the regularity and that the glass should be examined by holding it up to the light to see if it has internal strain lines. there was further communication over this lathe, and in 1638 the Amsterdam optician was to send Descartes a wooden model. When he went to Amsterdam to examine the finished machine for himself, Descartes was told that the workman needed time to make the copper and steel parts, and that others were building similar machines and would claim patent rights in Holland. Meanwhile Mersenne had written to Descartes to say that Armand Jean du Plessis, Cardinal-Duke of Richelieu and of Fronsac, the lead antagonist in Alexandre Dumas's The Three Muskateers, wished to be taught how to make lenses. If the lathe model succeeded, Descartes would try to obtain for him, presumably Mersenne, the privilege of monopoly in France. By the end of the year, Descartes had heard that someone in Naples was making, or had made, the same type of machine.

A lawyer living in the old glass-working city of Nevers, de Meru, wrote to Mersenne in 1646 announcing his lathe that could turn small glasses.[213] A replica of the machine was later delivered to the natural philosopher Pierre Petit in Paris, who although he stored it untested in his attic, made its existence known to Auzout, from whom news passed to Burattini in Poland. In Paris, de Ville-Bressieux had constructed seven machines, of which three were for concave hyperbolic, three for convex hyperbolic, and one for spherical lenses. He was asking for good glass, this being no longer readily obtainable from Venice.[214]

The reputations of Descartes and Mydorge led to their being invited to England. This never came to pass, but several English virtuosi were encouraged to construct their own machines for grinding hyperbolic lenses. The natural philosopher and mathematician, Isaac Newton, pursuing his optical researches at Cambridge, tried grinding non-spherical glasses, probably around 1666, after reading Descartes' *Dioptrique*.[215] He went so far as to sketch a machine for the purpose, before losing interest. In London, Sir Robert Moray, then Vice-President of the Royal Society encouraged a Frenchman named Monsieur de Son in lens work. In 1664/5 Moray himself was writing to Huygens on this matter. In 1665 de Son was reported to be 'zealously working at the preparation of parabolic lenses by a strange method'.[216] De Son laboured at his lenses, one of Venice crystal, the other of common glass, but they were never quite ready. There was some dispute as to their true form, whether they were hyperbolic rather than parabolic, before the whole matter faded, without any clue as to his method.

Francis Smethwick was the next figure to come to public attention for his machine work. Smethwick devised a machine for grinding hyperbolic lenses that attracted members of the Royal Society. Smethwick's vital dates are uncertain and he may be confused with a working optician of the same name. Hartlib describes a Smethwick as 'one of Oughtred's scholars' and says that in 1656 he was living

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213 De Meru to Mersenne, 30 April 1646. **Mersenne** Letter 1465.
214 Beale to Hartlib, 22 November 1659. **HP Letters** 67/22/8B–9A.
215 I. B. Cohen (ed.), *Isaac Newton's papers and letters on natural philosophy and related documents*, Cambridge: Harvard University Press, (1978), 47.
216 Oldenburg to Hevelius, 24 November 1665. **Trinity Coll.** Cambridge, MS O.11a148; Oldenburg 2. Letter 461.

at Blackfriars.[217] On 10 February 1661 he was given a patent as Library Keeper at Westminster Abbey, paid at £20 per annum with commons, the last year payment was recorded being 1689; he probably died in 1690.[218] On 14 May 1666 he applied for, and was granted, a patent for 'grinding optical glasses in figures which are not spherical'.[219]

Smethwick, who was admitted as a Fellow of the Royal Society on 16 May 1667, was introduced in the account of his invention published in the *Philosophical transactions* of 1668 as:

> The ingenious and industrious Francis Smethwick Esq., FRS, having for divers years painfully searched after the way of grinding glasses not-spherical affirms that at length he hath now found it, for the proof of which he lately (viz. February 27, 1667/8) produced before the said Society certain specimena of that invention, which were a telescope, a reading and two burning glasses.[220]

The clergyman and natural philosopher John Beale, however, described Smethwick's glasses as 'wrought by Bayly.' It is possible the working glass-grinder Bayley was shaping glasses to Smethwick's instructions.

On 5 March it was ordered that Smethwick's glasses should be tested against ordinary glasses, and this was done during the following week. His 4 foot telescope had three non-spherical oculars and a spherical object glass; it was judged better than a slightly longer one with spherical lenses. The hand lens magnified clearly across its entire width, but only when viewed from one side, not from both, as was the case with spherical hand lenses. The burning glasses were also declared effective. Oldenburg reassured the natural philosopher Robert Boyle that the glasses had been carefully measured to check that they were not spherical.[221] Smethwick was encouraged to proceed with his trials. However, while Smethwick may have been controlling the profile of the formers, and was presumably paying for the lenses, the workman whose hand

[217] **HP Eph**. 29/5/104A.

[218] Westminster Abbey archives, Lease Book XVI, f.385[b], records the patent. An administration of the effects of Franciscus Smethwick, of St Margaret's, Westminster, was granted on 11 October 1690. **NA.** Records of the Prerogative Court of Canterbury, PROB 6/66.

[219] Patent No. 149, granted 12 April 1667. **NA.** PRO: SPD Entry Book 25, 5.

[220] F. Smethwick, 'An account of the invention of grinding optic and burning glasses, of a figure not spherical ... ', *Philosophical transactions of the Royal Society*, 33, (1667/8), 631–2.

[221] Oldenburg to Boyle, 3 March 1667/8, **RS** MS OB no.83; Oldenburg to Boyle, 10 March 1667/8, **RS** MS OB no.84; Oldenburg 4 Letters 804, 808.

was on the grinding tools had been that of Bayly.[222] For more on Bayly (or Bayley) see Richard Reeve in Chapter Seven.

Hard on Smethwick's heels, the natural philosopher Robert Hooke then proposed a new way to grind lenses. Oldenburg confided to Hevelius in 1664 that ‘a certain famous Englishman, a fellow of the Royal Society' was working at a new way of polishing lenses; this was a veiled reference to Hooke. ‘It consists in this:’, he wrote,

> by means of one of those machines of the same kind [as Campani's] one can make such glasses as may be used in telescopes of any desired length both more accurately and more speedily than hitherto has been done.[223]

According to Peiresc, Drebbel had a grinding machine in London so simple in its construction that he could leave a boy to operate it, this because the lenses were secured on the machine in such a way that they needed no manipulation, and enabled several lenses to be made to exactly the same figure.[224] It is thought that Robert Hooke, who was well acquainted with Drebbel's daughter and her husband, adapted this lathe for his own use. It may have been that illustrated in his *Micrographia* of 1665.

The architect Sir Christopher Wren's method of grinding non-spherical lenses was announced to the Royal Society in 1669, some years after its development. A model of his machine was produced for the Society's inspection and his method was published in 1669.[225] Burnett writes,

> Although there is some evidence that Wren actually sought out an instrument-maker to realize a version of his machine, the diagram presented in the *Transactions* is not a machine at all but a representation of the geometry that underlies the proposal[…] Wren’s device, like other mechanical systems for making lenses, was never realized, not because the machine would not work in the mind, but because it would not work when brought into the realm of the wooden wheel and the brass cog.[226]

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222 Beale to Hartlib, 18 January 1660. **BL**, MS Add. 15948 f.93.[V]

223 Oldenburg to Hevelius, 13 November 1664. **BN** NaL 1641, ff.3–4; Oldenburg 2 Letter 352.

224 **Bibl. Inguimbertine**, Peiresc 1776 ff.412v, 413 [Life of Drebbel].

225 C. Wren, ‘An engine for grinding hyperbolic lenses’, *Philosophical Transactions of the Royal Society*, 4 (48), (1669), 961–2.

226 D. G. Burnett, *Descartes and the hyperbolic quest: Lens making machines and their significance in the seventeenth century*, Philadelphia: American Philosophical Society, (2005), 94.

Machinery constructed to the necessary level of accuracy and precision, built of materials unaffected by temperature and humidity, lay some distance into the future. All these devices failed to meet expectation, and do not seem to have brought any changes to the optical trade.

Chapter Six
The networks of correspondence

As telescopes and microscopes became known in Western Europe, references to their acquisition, what they could or could not reveal and how one compared with another, began to appear in the correspondence of virtuosi, military men, courtiers and diplomats of many hues. Their letters convey requests for instruments, or for the glass to make one's own lenses; news of technical developments; where instruments could be bought and at what price, with comments and criticisms. By the 1650s private and government postal services, some available to the public, were developing across much of Western Europe, alongside the improvement of roads and coastal shipping services. Such services were impeded by censorship, wars and the outbreak of fighting, but apparently less than might be imagined.

Much of this exchange was propelled by the correspondence of a few nodal figures who served as 'intelligence brokers.' These individuals were industrious in gathering information from their own acquaintances and passing it on to other centres from which it was dispersed or again passed on. A remarkable amount of copying went on—for some letters were replicated in full, others excerpted. These brokers did not themselves make great discoveries or write influential books, nor were they particularly concerned with optical instruments. Rather, it was their breadth of interest, their facility with languages and a willingness to disregard politics and religious persuasion, which gained them so many correspondents.

Many of the correspondents met in person at least once, in some cases regularly. In France the landed and legal classes moved seasonally between their country houses and the seats of provincial or national parliaments. It was their awareness of being away from the scenes of action that fired their pleas for news—any and all news—of ongoing discoveries. In England, in the fluid political situation then obtaining, Puritans, Catholics, even men of orthodox views, could find themselves at risk of arrest when the regime changed. Flight to the continent was the best line of escape. Catholics often made their way to Italy where sympathy with the relics of the House of Stuart extended to its supporters. In Florence, Padua or Rome they called on virtuosi such as the Italian scholar Galileo Galilei and his assistant Evangelista Torricelli, later on the eminent German polymath Athanasius Kircher. Protestants tended to seek refuge in those parts of the Low Countries where they found numerous like-minded colleagues and from where it was easy to return when the time was ripe.

The three 'brokers' examined here: natural philosopher Marin Mersenne, educational reformer and writer Samuel Hartlib, and secretary to the Royal Society Henry Oldenburg, have been chosen for the availability of their correspondence and the contacts mentioned are only those persons encountered in earlier chapters. Various informal gatherings or proto-societies can be identified prior to these great episodes of correspondence, while the dominance of the hand-written letter was reduced when the establishment of formal societies gave rise to printed journals.

At the beginning of the seventeenth century the astronomer Nicolas-Claude Fabri de Peiresc was the chief link between the academies of Italy and those of Paris. Peiresc had sojourned in Padua, knew the libraries of Florence and Rome, and was familiar with the physicists there and in Naples. His own home became a site of pilgrimage for travellers, among them Athanasius Kircher, Marin Mersenne; the French astronomers Ismaël Bouillau (or Bullialdus) and Pierre Gassendi; the British historian William Camden; and patron to the sciences Henri-Louis Habert de Montmor who was a wealthy lawyer and friend of Descartes. They were eager to know what observations were being made between 1610 and 1612 with Peiresc's five telescopes, received from Galileo. After his death, Gassendi's *Life of Peiresc*, published first in Latin, with an English translation in 1657, enjoyed a very wide readership. The numerous bound volumes of Peiresc's documents are now in the Bibliothèque Inguibertine, in Carpentras. Contemporary with Peiresc's gatherings in Provence, a group of enthusiasts met at the Paris house of the brothers Pierre and Jacques Dupuy, both scholars, for whom Bouillau served as librarian. Bouillau, born into a Calvinist family, converted to Catholicism in 1626 and moved to Paris in 1631. He travelled to Italy, the Levant and to the German-speaking regions and the Low Countries. He left an extensive correspondence, now in the Bibliothèque Nationale, with lesser holdings in the Paris Observatory and elsewhere.[227]

Marin Mersenne

Marin Mersenne was born into a humble family and attended the Jesuit college at Le Mans from 1604. Descartes attended the same college but the two are unlikely to have met due to their difference in age. Mersenne took his vows as a Minim in 1612 and after several moves, settled at the new convent of the Place Royale in Paris in 1620.[228] His situation was unusual in that he was the only cleric in France or in Italy to take part in these informal academies. Free of duties apart from his devotions, he undertook a vast correspondence ranging over philosophy, theology,

[227] R. Hatch, *Ismaël Boulliau (1605–94) astronomer, savant: An inventory of the Collection Bouillau*, Philadelphia: American Philosophical Society, (1982).
[228] J. R. Armogath, 'La groupe de Mersenne et la vie Parisienne', *XVIIe siècle,* 175, (1992), 131–9.

mathematics, physics, natural sciences, mechanics and music. He worked for the union of churches and saw no threat to his faith in his friendship with cardinals, Protestants, Socinians, reformers and materialists. All his letters incoming and outgoing were read by the *Correcteur* or supervisor; the content had to be restricted to the topic, with no mention of himself or of the business of the Minims or the convent. Mersenne sought and was granted access to forbidden books, though in 1635 he was denied access to a book on astrology. No visitors were admitted to his unheated cell; they met in the porterage rooms, which were at least warmed.

Figure 35: Portrait of Marin Mersenne, engraving by Balthasar Moncornet. Mu, New York Public Library, digital ID 1270352: digitalgallery.nypl.org, CC-PD-Mark.

Mersenne seldom ventured out of doors, other than to make a few experiments in fine weather. However he went to take the waters at Spa in 1629, and continued to Holland where he met Beeckman. In the winter of 1644–45 he was in the Minim convent in Rome where he met the Jesuit Kircher, Vatican librarian Lucas Holsten (or Lukas Holste) and fellow Minim philosopher Emanuel Maignan. At Florence, on the way back he met disciples of Galileo, among them Torricelli. Always in poor health, Mersenne caught a chill while meeting with Descartes in Paris and died in September 1648. After his death a telescope he owned passed to his doctor. Most of his letters were preserved and bound by the Minims, though some of those from Descartes were returned, and one volume of bound letters was later lost. Mersenne's correspondence from 1617 to 1648 was published between 1932 and 1988.[229] On learning of his death, an acquaintance wrote of him:

> The first of this month was the end of the life of the Huguenot Monk, your admirer and friend, to wit, Father Mersenne[…] You know that he did not believe all his religion[…][230]

The group which was drawn to Mersenne from about 1635 until his death included mathematicians Charles Cavendish and René Descartes; the astronomer Pierre Gassendi, philosopher Thomas Hobbes, Constantyn Huygens then secretary to Prince Frederick Henry of the Orange family; and natural philosopher Pierre Petit.

[229] *Correspondance du P. Marin Mersenne …* , various editors and presses, Paris, (17 vols., 1932–1988).

[230] André Pinot to his uncle, Pasteur Rive, 11 September 1648. **Leiden** B.P.L.IV, 386 f.60.

Correspondents whom he never met included Galileo, the astronomer Johannes Hevelius and Theodore Haak, a German of Calvinist parentage from Neuhausen. In 1625 Haak had studied in England, then toured the continent before settling in London from 1629. He was the principal channel between Mersenne and the northern lands, linking Pell and Hartlib to the Parisian hub before the days of the official societies.

On 1 February 1629 Mersenne wrote in correspondence to Galileo on his collaboration with the mathematicians Claude Mydorge and Descartes on the template for Descartes' hyperbolic lenses. Descartes told him of Beeckman's visit in 1628 and served as a channel of communication between Mersenne, Charles Cavendish and Thomas Hobbes. Cavendish's own network reached out to the mathematicians William Oughtred, Walter Warner, Mydorge and Gassendi, and the Hamburg mathematician and philosopher Joachim Jungius.[231]

Descartes made frequent reports to Mersenne on the problems with his craftsmen. Frustrated by what he supposed to be their lack of skill or perseverance, Descartes had little time for the success of others. In 1638 he advised Mersenne not to believe all he heard about the marvellous telescopes from Naples—the work of the Italian lawyer and astronomer Francisco Fontana. Descartes further alleged that most of these men were charlatans, as was mathematician, engineer and musician Jean le Maire. Writing to Mersenne, Descartes claimed that le Maire, a friend of the Minim scholar, was given to exaggeration.

By February 1639, however, he had mellowed, and now considered Fontana's lenses to be hyperbolic. According to Descartes if Fontana did not get the idea from his *Dioptrique*, he could have learnt from a young instrument maker named Ferrier and others who knew of it twelve years before.[232] Others were making or attempting such lenses. The mathematician Florimond de Beaune speaks of Fontana's machine as nearly finished and with the hope that in a few days he might begin work on hyperbolic lenses. By November 1639 Mersenne had been able to try some of Fontana's seven-and-a-half foot telescopes, which had come from Florence. These, he wrote to Haak in London, were over-rated. An idea of the outlay required by private individuals comes from another letter to Haak, December 1639: Daniel Aubery, son of the ambassador to Holland, who has already made a two foot telescope, now yearned to make 'conical-lens' telescopes, that is, with a hyperbolic lens, for himself and his friends. He had built a forge, prepared 200 files, and hired two or three craftsmen to help him.

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[231] J. Jacquot, 'Sir Charles Cavendish and his learned friends', *Annals of science*, 8 (2), (1952), 13–27.

[232] For a discussion of Ferrier's identity see D. G. Burnett, *Descartes and the hyperbolic quest: Lens making machines and their significance in the seventeenth century*, Philadelphia: American Philosophical Society, (2005), 1–4, 1, ft. 1.

On his visit to Italy, Mersenne was eager to acquire lenses made by Torricelli. However, when the opportunity came, he realised that he could not afford them, and therefore chose the two least good on offer, bargaining that he would obtain glass from Venice for Torricelli in part payment. This he did, but as his acquaintances feared, he was dissatisfied with the performance of the two poor-quality lenses and critical thereafter of all telescopes.

In 1646 de Meru, a lawyer of Nevers, wrote to Mersenne about his lathe for grinding hyperbolic lenses. De Meru had set up his lathe with a tool to shape the glasses directly, without intermediary formers. However, he seems to have thought it adequate to shape them to a large diameter sphere, believing that this would approximate to a hyperbolic curve. The machine is of interest here because de Meru sent some of his lenses, and later a replica of his lathe, to Pierre Petit, a Parisian government official with a practical interest in astronomy. Petit lodged the lathe in his attic and failed to experiment with it but he did mention it to Huygens and the astronomer Adrien Auzout. Word passed from Auzout to the Polish instrument-maker Tito Livio Burattini and thence back to Boulliau in Paris. Mersenne circulated both fact and gossip concerning the grinding of lenses, in particular with regard to that perennial bone of contention, the possibility of grinding a non-spherical lens. Following Mersenne's death, Montmor played host to Bouillau, Descartes, Hobbes, Gassendi, Oldenburg and the physicist Baltasar de Monconys at his houses in and outside Paris.

Samuel Hartlib

The expert author Samuel Hartlib was born at Elbing in Prussia and settled in England in the late 1620s. From England he maintained a correspondence with fellow-protestants scattered across northern Europe. His concerns for the betterment of mankind generally embraced education, theology and agriculture, besides what would now be described as technology. His interest in optics, while it included telescopes and microscopes, extended into the application of lenses to lamps and in window-panes.

Hartlib's correspondents on optical matters included the clergyman and natural philosopher John Beale, with whom he discussed telescopes; the protestant pastor and alchemist Johann Moriaen in Amsterdam, thought to have practiced as an optician in his earlier years at Cologne; Johan Wiesel, optician of Augsburg; and the mathematician John Pell, whose interest in optical matters remained throughout his residences in the Low Countries and Geneva. Benjamin Worsley a political economist with a taste for astrology, and a self-declared collector of 'novelties' in all fields of arts and sciences, supplied more information on the activities of the astronomer and politician Sir Paul Neile and the instrument-maker Richard

Reeve.[233] The mathematician Nicholas Mercator wrote of the celebrated optician Daniel Chorez,[234] as did the alchemist Erasmus Rasch whose letters from Paris convey news of Chorez and of Johan de Wyck of Delft, lens grinder and maker of brass basins. The puritan William Speed's letter of 1631 conveyed the first news of Neile's burgeoning interest in 'learning'. George Horne, doctor of divinity and public professor of history at the University of Leyden was another informant on microscopes. The German astronomer Johannes Hevelius, towering over the dilettanti, was equally happy to correspond with Hartlib on telescopes.

The Hartlib papers, now in the University of Sheffield, available on CD-ROM and online, contain numerous anonymous extracts and copies of letters to and from third parties.[235] From these, and from *Hartlib's ephemerides*, a series of jottings made over many years, emerge news of optical matters both abroad and close to home. Indeed in some cases conveyed by visitors to Hartlib's house. Thus he notes the French mathematicians Mersenne, Gilles de Roberval and Descartes; Fromanteel—possibly Ahasuerus Fromanteel, a clockmaker with an interest in microscope lenses who spent time in London and in the Low Countries, as did his sons; Stephan Keus, otherwise known as Stephanus Coes, a manufacture of telescopes, optical instruments and clocks from Amsterdam;[236] the natural philosopher and administrator (Sir) William Petty; the Hon. Robert Boyle, a giant among contemporary natural philosophers; the mathematician William, 2nd Viscount Brouncker; Hartlib's son-in-law Peter Figulus; Etienne de Ville-Bressieux, optician and mechanic; Joshua Childrey, antiquary and one who frequented Reeve's shop; the inventor Cornelis Drebbel and his sons-in-law the Kuffler brothers, all engaged in lens grinding and other mechanical matters; Thomas Henshaw, diplomat and possessor of fine telescopes; Samuel Karl Kechel, curator of the instruments at Leiden University; Dudley Palmer, lawyer and collector of telescopes and microscopes; the doings of Francis Smethwick, mathematician and professed grinder of non-spherical lenses, are recorded, as is the interest of Sir Thomas Wendy, medical practitioner, also the activities of John Wallis, Savilian professor of geometry at Oxford and a founding member of the Royal Society; and the architect (Sir) Christopher Wren, much concerned at the time with lens grinding.

Hartlib's correspondence and Ephemerides disclose a London with a fair number of lens grinders who can deliver smallish telescopes and simple microscopes, and

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[233] See Chapter Four for Reeve's work with Charles Cavendish and Chapter Seven for biographical detail.
[234] See Chapter Three for more on Chorez.
[235] **HP Letters**; *The Hartlib Papers:* 2 CD-ROMs, Ann Arbor, (1995); enlarged edn., Sheffield, (2002): https://hridigital.shef.ac.uk/hartlib/ [accessed August 2016].
[236] C. Webster, book review of 'The Correspondence of Henry Oldenburg', *British journal for the history of science,* 3, (1966), 79–80, on 80.

where a few craftsmen are able to prepare the more difficult and costly long-focus lenses for big telescopes. It is a London where men of learning and culture enjoy building up their own collection of optical instruments, clocks and watches, seeking to possess the finest examples available. If they travel abroad—as many did—news of similar instruments circulating on the continent is reported on return. Hartlib is a broad conduit for optical news; the survival of his papers, with the diaries of diarists John Evelyn and Samuel Pepys, shows how important the lens business was in the early days of the Spectacle-makers Company.

Henry Oldenburg

Figure 36: Portrait of Henry Oldenburg by Jan van Cleef, original oil painting held by Royal Society, London. Wikimedia Commons, CC-PD-Mark.

Henry Oldenburg, was the son of a teacher in Bremen, an important trading port some fifty miles up-river from the North Sea. Having graduated with a Master's degree in theology, in 1641 he decided to travel to the Low Countries for further education, settling in Utrecht. [237] It seems likely that he then acted as tutor to the sons of various noble or merchant families, for he travelled in France, Switzerland, Italy and Holland and probably visited England, becoming fluent in these languages. During these years he met many people with whom he was to maintain a long-term correspondence. He also became friendly with the Boyle family, Earls of Cork, especially Robert Boyle and his sister Lady Katherine Ranelagh. This brought him into government circles and he was recruited to carry diplomatic messages between Cromwell and the City of Bremen. About this time also he met Hartlib in London.

In 1656 Lord and Lady Ranelagh retained him as tutor to their son Richard Jones, whom he was to accompany round the continent for the next four years. While the boy studied, first in Oxford then at Protestant colleges in Saumur and later Montpellier, Oldenburg was able to meet a wide variety of natural philosophers, chemists, physicians, and theologians, many of whom were added to his regular correspondents. Oldenburg and his pupil toured through Germany and came back

[237] M. B. Hall, *Henry Oldenburg: Shaping the Royal Society*, Oxford: Oxford University Press, (2002).

to Paris where they attended meetings at several of the informal academies flourishing in the city. The Hôtel du Thou housed the great library amassed by the historian Jacques-Auguste de Thou and amplified by the collections of his librarians Pierre and Jacques Dupuy. The meetings in this house attracted men of letters, lawyers, and intellectuals of all sorts. After 1647 the meetings continued under Jacques de la Rivière, who succeeded to the librarianship of the Hôtel du Thou and with whom Oldenburg remained in contact. During Oldenburg's year in Paris, the academy most concerned with natural philosophy was that organised by Montmor. It attracted mathematicians, medical men and those interested in pneumatics—experiments with the air-pump.

Back in England, Oldenburg was lodging with Hartlib during the excitement of the Restoration of Charles II of the House of Stuart to the throne. It was also the year of the foundation of what became the Royal Society, Oldenburg himself being elected a member in December 1660. Oldenburg is well-known as the first Secretary to the Royal Society but his published correspondence begins in 1641 when he was still active on the continent. In 1664 a protestant, Henri Justel, who had inherited the post of Secrétaire du Roi from his father and one of whose duties was the licensing of books, approached Oldenburg. Justel offered to exchange scientific news and to procure books for the Royal Society. His offer was taken up and thereafter he was the most diligent transmitter of information to Oldenburg, and the man principally responsible for disseminating news of English books and science into France and beyond, into a wider Europe.

From about 1664 Justel held frequent meetings at his own house where foreign merchants, embassy staff, students and gentlemen on the Grand Tour mingled with the scholars and scientists of Paris and the provinces. Auzout, Bouillau, Huygens and Petit were regular attenders, as was Guillaume Ménard,[238] an optician working in Paris from about 1660. For the first time we hear of a French craftsman being welcomed into these élite gatherings. Among the numerous Englishmen calling on Justel, usually bearing letters of introduction from Oldenburg, were Christopher Wren, Pepys, the astronomer Edmond Halley, and Robert Bruce, 1st Earl of Ailesbury, then resident at Montpellier. Ultimately, almost all Oldenburg's foreign news came via Justel. One source of this foreign news was the churchman and scholar Pierre Daniel Huet who established the Caen Académie in 1662 and whose links with England were through Justel. Huet, commissioned to obtain a microscope in Paris, reported that those by Reeve were the best available though, at five or six louis, far more costly than those of Ménard at eighteen francs.

Oldenburg comes into the picture just when virtuosi and craftsmen in London and

[238] M. Morizet, 'Do you know the Ménards? A dynasty of Parisian opticians in the 17th and 18th centuries', *Bulletin of the Scientific Instrument Society*, 106, (2010), 13–15.

Paris were striving to build very long telescopes. There is much competition, and not a little boasting and downplaying of the other side's achievements. The much-travelled Oldenburg comments on his visit to Augsburg where he met Wiesel. Further, he is a channel for news of lenses emanating from the workshops of Eustachio Divini and Giuseppe Campani. He is familiar with the Paris optician Chorez, and with Bressieux—always about to deliver a non-spherical lens. Regular letters flow between Oldenburg and Auzout, who writes optimistically about the new fine glass said to be available in Paris and Lyons, only to have his hopes dashed when the samples turn out to be still inferior to that from Venice. When Auzout criticises Hooke's grinding machine as 'impractical', it is Oldenburg who has to smooth ruffled feathers. Oldenburg's correspondents include major scientific figures—Huygens, Hevelius, Boyle—but optical matters also figure in letters to and from diplomats, travellers and other lesser men.

The conflict between England and France which began about 1688 and lasted until the Peace of Utrecht in 1713 reduced the flow of ideas from France to almost nothing, a state of affairs confirmed by the naturalist and physician Martin Lister who accompanied Hans William Bentinck, 1st Earl of Portland to Paris; in his account, published in 1698, Lister reported a great ignorance of England and its affairs.

Chapter Seven
The London trade

Chapter Four detailed correspondence between the mathematician Thomas Harriot and astronomer Sir Christopher Heydon in 1610 that provides the earliest evidence of English-made spy-glasses. Christopher Tooke, a talented lens grinder who appears to have worked at Syon House, upstream from London, from 1604/5 onwards is now recognized as Harriot's main assistant, and significantly responsible for the technical work. As Chapter Four documented, politician Robert Killigrew's despatch of a perspective glass to the ambassador Sir Dudley Carleton in 1618 also hints at a London origin, when the accompanying letter refers to 'workmen who[...] have ground me forty glasses before I could have such as would serve[...].'[239] Carleton's workmen were anonymous; the first named optician is one Bates of Tower Hill, whose perspectives were advertised in a book on seamanship in 1626, but who is otherwise unknown. The soldier Sir Thomas Hutchinson received a draw telescope from his son John in August 1638. The covering letter, sent from London, informed him

> I have sent you a perspective glass. Sir John and my cozen Tho. Byron chose it, it cost 2 pieces[...] there is two glasses, one is to look at the moon, and it has an m upon it. When you look with that glass you must draw the first draught to the circle, which is marked with an m. If you put in the other then draw it no further than the first circle. All the rest of the draughts remain at the same distance for both glasses.[240]

As mentioned in Chapter Four, the group of spectacle-makers concerned with setting up the Spectacle-makers Company may have made spy-glasses, however they probably dealt first with eyeglasses, hand lenses, and burning glasses, and second with watch glasses and bull's-eye glasses for lanterns. Some hints of the trade emerge from the Spectacle-makers Minutes of the 1660s reporting searches of workshops, probably a continuation of an earlier practice with previous records lost in the Great Fire. The most common offence was the vending of spectacles made 'of looking glass wrought only on one side', that is, plano-convex lenses, and fines as high as twenty shillings were imposed on craftsmen found to have these in their shops. We also learn of the wives and girls employed to grind watch

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[239] Killigrew to Carleton, 14 September 1619. **Cal. SPD.** James I, 110 (1619–23), f.92.
[240] L. Hutchinson, *Memoirs of the life of Colonel Hutchinson*, London: Routledge, (1906), 388–9.

glasses.[241] Emissaries from the Spectacle-makers Company raided The Haberdashers, who counted spectacles among their items of trade. These raids confiscated and destroyed not only spectacles with plano-convex lenses, but also those made of French glass.

Richard Reeve

Initially, good quality telescope lenses of long focus had to be obtained from overseas. The first London opticians who seem to have been both competent and willing to attempt large radius objective lenses for astronomical telescopes were Richard Reeve of Long Acre[242] and a certain 'Bayly.' This latter may have referred to John Bailey, or Bayley, known to have been working between 1627 and 1634, perhaps related to another Bayley, working between 1660 and 1671, and in 1663 located at St Paul's Churchyard.

The exact identity of Reeve, and his status in the optical trade, remains obscure. It is believed that he originated from a Berkshire family, but nothing is known of his schooling or any apprenticeship. Since he was in business in the parish of St Paul, Covent Garden, outside the City of London, he was not obliged to be a freeman in any of the City guilds. It is noteworthy that Reeve is frequently referred to as Mr Reeve, whereas that mark of respect is never accorded to Bayley, the working glass-grinder. It is evident Reeve had the education, the capital, and the workmen, to undertake orders which were extremely difficult and time-consuming to execute. He was first mentioned in a letter to Samuel Hartlib in 1639, after which he figures prominently in accounts of telescope and microscope manufacture. It seems unlikely that Reeve was a spectacle-maker by trade for in 1641 Hartlib, speaking of the manufacture of brass, noted:

> L'ottone, Latton or Pinbrasse is made of copper much augmented by the addition of Lapis Calaminaris (a stone found in the bottom of leadmines)[...] Mr Reeve, the curious Turner of London, first found of this stone in Darbishire when others thought it was nowhere else to be found in England but in Devonshire:[...] he first set men at worke to gather and calcine it there: and after taught others the making of Latton wire whereof they make pins[...].[243]

In 1652 John Evelyn referred to him as 'famous for perspectives and turning

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[241] **London,** MS GL 5213, Spectaclemakers' Minutes, vol. 1.
[242] For what is known about Reeve I am obliged to Dr Allen Simpson, notably his 'Richard Reeve—the 'English Campani'—and the origins of the London telescope-making tradition', *Vistas in astronomy*, 28, (1985), 357–365, amplified by his later researches and personal correspondence.
[243] **HP Eph.** 30/4/78A–B.

curiosities in ivory';[244] while in 1660 Hartlib commented on 'Mr Paston's perfuming box finely turned by Mr Reeves[...]'[245]. Writing to Hartlib, the clergyman and natural philosopher John Beale expounded the use of ivory in telescopes:

> To fit it[...] ye concave glasse being excellent should be put into an ivory box, (rather than silver or gold) of lesse than an inch length, to be covered on ye outside with an ivory scrue for defence, it being so thin as may be easily broken.[246]

Whatever his trade or calling, an impressive list of virtuosi, men of affairs and foreign visitors, called at Reeve's shop, among them mathematicians Charles Cavendish, Walter Warner and John Pell, whose relations with Reeve were recounted in Chapter Four, and over the years, the natural philosopher and physician, Henry Power; patron of the sciences, Sir Paul Neile;[247] antiquary and astrologer, Joshua Childrey; mathematician, James Gregory; naval official and diarist, Samuel Pepys; natural philosophers Robert Hooke and Christiaan Huygens, astronomer and astrologer, Thomas Streete, philosopher Thomas Hobbes and the physicist Baltasar de Monconys. In September 1649 Johan Wiesel, optician of Augsburg, sent to Amsterdam a day-and-night telescope costing 240 guilders, for the political economist and collector Benjamin Worsley. This telescope consisted of an eleven-draw tube furnished with seven lenses.[248] Its arrival in London was something of an event; in early December Neile went to Hartlib's house 'to see the Augsburg-Glasse having great skil in opticks'.[249] Inspired by the performance of the glass Neile urged Reeve to produce as good an instrument.

Hartlib's ephemerides reveal that, in 1649,

> Reeves, Serson and one more by way of partnership are upon a great design at Kingston upon Thames to perfect the optical glasses. The instruments are made and very promising but the effect is yet to be expected.[250]

Neile and Reeve were close collaborators in the matter of large-lens telescopes,

> and having instructed Reeves who is the only Mechanical Man for turning of Glasses they are now persuaded they shal make such Optical Glasses the like have never beene and that shall far exceed the best of the Augsburg-Opticus,

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[244] E. S. de Beer, *The diary of John Evelyn*, Oxford: Clarendon Press, vol. 3, (1955), 64.
[245] **HP Eph.** 29/8/1.
[246] ?Beale to Hartlib, undated. **HP Letters** 8/56/1A–B.
[247] Contemporary spelling varies: Neale, Neal, Neile. See also A. D. C. Simpson, 'Sir Paul Neile', in O*xford Dictionary of National Biography*, (2004).
[248] **Wolfenbüttel,** Cod. Guelf 98 Novi f.308.
[249] **HP Eph.** 28/1/36B.
[250] **HP Eph.** 28/1/23B.

> Sir Paul bending all his strength that way.[251]

The task must have called for a good deal of effort, persistence and, not least, money. In 1650 Reeve was at White Waltham, Neile's Berkshire property, preparing lenses to Neile's directions for Seth Ward, Savilian Professor of Astronomy at Wadham College, Oxford. Hartlib kept a note of the proceedings: in January [1651]

> Mr Williamson of Gray's Inne came to me... telling me that Sir Paul Neale was mighty busy with Mr Reeves about the Perspective Glasses and hoped to be at a certainty in March next, that either he had obtained that which he promised or a rational account why when I could reach the end.[252]

Worsley reported to Hartlib that 'Sir P Neile hopes about midsummer to come to a perfect trial or experiment with his optical tubes Reeves being continually with him.'[253] In fact Worsley had sold the Wiesel telescope in February 1650 to Dudley Palmer, lawyer and virtuoso, who already possessed '15 or 17 perspectives also microscopes and a world of other rarities'.[254]

Reeve also made 35 foot telescopes for Neile himself, and for the architect Sir Christopher Wren when the latter was appointed Professor of Astronomy at Gresham College in 1657. This telescope was demonstrated to Charles II in October 1660. It pleased the king so much that another was made for him and installed at Whitehall Palace garden. It may have been this that Worsley referred to in a letter to Hartlib in the spring of 1653, writing: 'Reeves and Sir Paul Neale have found out a new kind of telescope which is said to excel all others whatsoever.'[255] Yet we never learn whether this 'new kind' refers to the figuring of the lens or lenses, or their arrangement within the tube. Other telescopes were made for Neile's collaborator the astronomer William Balle, and as diplomatic gifts, for Pope Alexander VII born Fabio Chigi and to Charles's brother-in-law the Duke of Orléans, Phillipe I of the House of Bourbon.

In 1655 Hartlib reported that Wren judged Reeve the best maker of microscopes.[256] This judgement is ambiguous; either Reeve was the best in London, or his technique had advanced over that of Wiesel. The latter had supplied two microscopes to Robert Boyle in 1650 and which according to Hartlib, 'we enjoyed exceedingly and which are in truth far better than all such instruments

[251] **HP Letters** 28/1/73B–74A.
[252] **HP Eph.** 28/2/4A.
[253] **HP Eph.** 28/2/14A.
[254] **HP Eph.** 28/1/50B.
[255] **HP Eph.** 28/2/58A
[256] 7 September 1655. **HP Eph.** 29/5/46B.

hitherto invented.'[257] In 1660 Reeve tested telescopes belonging to Childrey.[258] The 1661 transit of Mercury was observed from Reeve's shop, most likely from his rooftop by Streete and Huygens, and other interested persons.

Samuel Pepys was well acquainted with both Richard Reeve senior, and his son, also Richard Reeve, who in 1660 had delivered 'a little perspective, it cost me 8s,' intended for William, 2nd Viscount Brouncker. Pepys frequently called on Reeve to look at or buy microscopes, spy-glasses, and larger telescopes; and Reeve, who valued Pepys' custom, particularly as he often bought on behalf of other people, would call on Pepys at his house. On 24 July 1664 Pepys decided to buy a microscope and he called at Reeve's shop, only to find him absent. The following day, Reeve presented himself and they returned to the shop where Pepys chose his microscope, but this seems to have been either a sample or an unfinished piece, as Reeve delivered the microscope on 13 August, adding as a gift a scotoscope—a water-filled glass globe which focused the light of a candle onto the specimen being examined under the microscope.[259] The custom of adding a lesser instrument as a bonus to purchasers seems to have been general practice in the seventeenth century. Pepys recorded that Reeve brought along a twelve-foot telescope on 6 August 1666. However, they were unable to test the instrument as the night proved cloudy. As Reeve stayed overnight, they were able to share 'a good discourse[...] concerning glasses' and the following day Reeve brought along two telescopes, of twelve and six feet length. The sky was clear and Pepys was so enthralled by what he could see that he bought the larger of the two instruments.

Baltasar de Monconys, a native of Lyon educated by the Jesuits, was part of Mersenne's circle of savants. The group included many Englishmen while Monconys himself travelled to England in 1663. In Oxford he called on Wren and Wallis, then in London he met the future members of the Royal Society.[260] On 23 May 1663 he could be found at Reeve's shop, looking at microscopes. Reeve gave him an eyepiece, but he apparently made no purchase on that occasion. He later went to Whitehall to see the king's telescope, made by Reeve to Neile's pattern, and declared it 'worthless.' From a man who had bought several telescopes and lenses from Eustachio Divini and Evangelista Torricelli, his opinion may carry some weight.[261]

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[257] Hartlib to Hevelius, 20 March 1651. **Paris Observatoire.** Hevelius AC 1.2 f.215v.
[258] Oldenburg to Saporta, 11 August 1659, referring to news in letters now lost. **RS** MS MM.1 f.57v; Oldenburg 1 Letter 152.
[259] M. H. Nicolson, *Pepys' diary and the new science*, Charlottesville: University Press of Virginia, (1965), 22–27.
[260] **Lyon**, MS 81 `Melanges sur Lyon', ff.44r, 51r, 53r.
[261] B. de Monconys, *Les voyages de M. de Monconys*, Lyon, (1665–6), 2, 28 and 77; A. J. Turner, 'Grollier de Servière, the brothers Monconys: Curiosity and collecting in seventeenth-century Lyon', *Journal of the history of collections*, 20 (2), (2008).

Henry Power, a naturalist, physician, and fellow of the recently formed Royal Society of London, latterly practising at Halifax, corresponded with Reeve using Tillison and his brother Thomas as carriers, and copies of two letters from Reeve, dated 11 and 16 March 1660/1, survive amongst his papers.[262] The second letter is accompanied by a price list. This includes 'telescopes with concaves', ranging from two inches in length, priced at ten shillings, to four feet in length, at two pounds; 'telescopes with convex inverted and erected', from two feet in length, at four pounds to thirty-six feet in length, at thirty pounds. There are also 'microscopes of several sizes', priced from three to six pounds. These prices were not mere extrapolations, by 1665 Reeve had produced a sixty-foot telescope, whose performance was discussed by Boyle and Oldenburg but judged to be only as good as shorter telescopes from the Campani workshop.[263]

In a letter to Reeve, dated 10 August 1662, Power wrote: 'I intended long since to be your chapman for a microscope and would very gladly have one as good as you can make it. I have perused many of your making and find none comparable to that you sold Sir Robert [Boyle...]'.[264] He then detailed the weaknesses of the microscopes as he perceived them: the extremely small field of view, the impossibility of placing any but the smallest objects under the lens, and some suggested improvements: enabling the distance between eyeglass and adjacent lens to be variable, providing a crystal object plate so that transparent objects may be viewed by transmitted light, providing 'various sorts of object glasses', because he believed that 'some may more distinctly represent some sorts of objects than others', and suggesting that two convex lenses might be as powerful as three. Power's letter continues with a request for an eye-glass for his telescope, perhaps to replace one that was broken, and to send a glass or two for his lesser telescope presumably supplied by Reeve 'which you know draws about 5½[...] I return to you many thanks for the reflecting plates you fitted to both my tubes, I am much pleased with them.'

Clearly several telescopes supplied by Reeve were circulating among Power and his northern friends, including the mathematician Richard Towneley who also possessed one by the much-admired Divini.[265] When the natural philosopher John Beale set down his thoughts 'concerning perspective tubes and telescopes' around 1660,[266] however, he had nothing whatsoever to say about Reeve's products. In eight numbered paragraphs, Beale noted that previously the best telescopes had

[262] **BL** MS Sloane 1326 ff.23a–24b.
[263] Boyle to Oldenburg, 9 December 1665, **RS** MS B 1 no.100; Oldenburg to Boyle, 19 December 1665, **RS** MS OB no.43; **Oldenburg** 2 Letters 469, 473.
[264] **BL** MS Sloane 1326 ff.31b–32a.
[265] C. Webster, 'Richard Towneley ... ', *Transactions of the Historical Society of Lancashire and Cheshire*, 118, (1966), 51–76.
[266] **BL** MS Sloane 548 f.18, 'Mr Beale concerning perspective tubes and telescopes.'

but two lenses, that it was now shown that four glasses, correctly ordered, performed better; that no crystal or Venetian glass was as good for telescopes as old Venice glass, especially that with a greenish tinge, consequently the great Divini used old mirror glass, though Stephan Keus (Stephanus Coes) of Amsterdam preferred to melt his own glass from river flints. Many artists had sought to make hyperbolic lenses but without success, hence (it appears, although the handwriting is in parts illegible) shorter tubes with seven lenses of Keus's glass would be an improvement. Beale ended with the striking phrase that the invention of Galileo 'made a fragment of glass of more value than the richest jewel.'

Christopher Cock

Figure 37: Eight-draw refracting telescope, by Christopher Cock, English, fourth quarter seventeenth century, © Whipple Museum, Cambridge, Wh.0286.

Richard Reeve was alive and well in December 1665 when he dined with Boyle at Oxford[267], but it is possible that he died in January 1666 (N.S.), the uncertainty arising from the common name.[268] It also seems that his son, who had been working with him, Pepys mentions 'young Reeve' in 1660 and 1661, was not up to the same standard as his father. A letter from Reeve to Hevelius, 24 July 1668,[269] is far less literate than those to Power cited above. It emerges, however, that he has 'glasses of 60 and 110 foot ready by[...]', possibly inherited from earlier times. Whatever the identity of this Reeve, the Royal Society soon abandoned him in

[267] 'Mr Reeves chancing when I was yesterday at Oxford to dine with me, I acquainted him with [Campani's glasses] ... ', Boyle to Oldenburg, **RS** MS B1 no.100; Oldenburg 2 Letter 469.
[268] A nuncupative will (one dictated to or overheard by witnesses but unsigned) of Richard Reeve, 'late of the parish of St Paul Covent Garden but obit Hampstead', January 1665/6.' It hints at an accident or sudden illness progressing so swiftly to death that no written testament was drawn up. Unfortunately the content of the document does not describe Reeve as an optician or turner.
[269] Reeve to Hevelius, 24 July 1668, **Paris: Observatoire** IX no.1297; Oldenburg 4 Enclosure 935a.

favour of Christopher Cock, also spelt Cocks, Cox, who may have been apprenticed to Reeve senior, and who was henceforth favoured with their commands and orders. David Gregory, experimenting with the reflecting telescope that now bears his name, wrote from St Andrews to the mathematician and scientific administrator John Collins in 1672, 'As for my experiment with Mr Reeves, he could not polish the large concave upon the tool.'[270]

In 1668–9 Cock made a sixty-foot telescope to Oldenburg's orders for Hevelius. His first attempt did not succeed, but by August 1669 Oldenburg was able to tell Hevelius that they had tested the lens, 'and the maker deserves praise for his skill'. Cock's bill was enclosed, for the sum of forty pounds for three glasses for a fifty-foot telescope. As tubes cost fifteen pounds, it was assumed that Hevelius would surely be able to obtain one more cheaply from his own craftsmen. In a post-script he explained that the objective had a focal length of about fifty feet, but the maker could not be expected to deliver exactly to order.[271] Hevelius was delayed by the difficulty of finding a workman to make the necessary tube and then again by the onset of summer, when the planets were not visible, but in August 1670 he reported back on the satisfactory performance of this telescope.

Hevelius bought a microscope from Cock that was so excellent that military reformer and deputy to the Polish parliament John Sobieski, later to become king of Poland, desired a similar instrument.[272] Hevelius wrote to Oldenburg in 1671 hoping that second instrument should be even better, but if it turned out so, he would to keep it for himself and pass his earlier one to Sobieski. Oldenburg accordingly contracted with Cock for a fine microscope at a price of ten pounds.[273]

Bayley and the virtuosi

Bayley's name is mentioned less frequently than that of Reeve, and as already noted Bayley is not accorded the honorific of 'Mr'. In March 1659 Beale, commenting to Hartlib about the progress being made with telescopes, adds, 'By the workman Bayly, yu may knowe whether hee knows of any further improvement made upon that kind of telescope.'[274] In February 1660/1 he further relates that he has sent to Reeve and Bayly for concaves and instructed his sister to

[270] Gregory to Collins, 23 September 1672, in **Rigaud.** vol. 2, 243–5.
[271] Oldenburg to Hevelius, 2 August 1669, **Paris: Observatoire** X no.8; Oldenburg 6 Letter 1262 and Invoice 1262a.
[272] Born into the Polish nobility, in 1676 he was elected king of the Polish-Lithuanian commonwealth, ruling as Jan III Sobieski.
[273] Hevelius to Oldenburg, 22 February 1670/1, RS MS H 2 no.24, Oldenburg to Hevelius, 18 April 1671, **Paris: Observatoire** X no.8; Oldenburg 7 Letters 1637 and 1680.
[274] Beale to Hartlib, 22 March 1658/9. **HP Letters** 51/99B–100A.

pay for these.[275] In 1671 John Flamsteed, later to become the first Astronomer Royal, wrote to Collins from Derby, 'Sir, I understand that one Bayly a glasse grinder workes glasses cheape.'[276] Beale also mentions Smethwick's glasses as being 'wrought by Bayley.'[277]

For those seeking to buy lenses for telescopes and microscopes during this period, Reeve and Cock appear to be the only professional opticians, in the sense that they kept shops, while probably employing workmen based elsewhere; Bayley was perhaps one such. At the same time, we learn of virtuosi in London and elsewhere in Britain who were busily grinding lenses for themselves. They had no other option. The mathematician and astronomer William Gascoigne wrote from Yorkshire to the mathematician William Oughtred in February 1641, describing his experiments using various perspective and spectacle lenses, that he was limited by lack of workmen to assist in making lenses or fittings.[278] The antiquary Christopher Towneley, son of the mathematician Richard Towneley, told Flamsteed, however, that Gascoigne's father 'was much given to mechanicks' and had a large house full of tools and contrivances, so we may suppose the son to be handy with tools.[279]

Thirty years later Edward Bernard a Royal Society Fellow and Savilian professor of astronomy at Oxford, could write to Collins that in Oxford 'patrons and tools are wanting, not willing and fit workmen. We lack a corporation, a set of grinders of glasses, instrument makers, operators and the like[...]'.[280] Collins patronised Cock; according to Flamsteed, '[...]a 7 foot glasse which Mr Collins procured Mr Cocks to grind thinner than usually, which is a very excellent one[...]'.[281]

Provincial virtuosi were, in fact, less isolated than their rural addresses might suggest, many being familiar visitors to Oxford and London. A group of northern Catholics, among whom was the former Jesuit Gascoigne, who had met Athanasius Kircher in Rome, and the Towneley family, of whom Richard had a consuming interest in optical matters, were no strangers to the European catholic community, their sons being generally educated at Douai or other continental seminaries, where they became acquainted with European savants and craftsmen. Those

[275] Beale to Hartlib, 17 February 1660. **HP Letters** 67/22/8B.
[276] Flamsteed to Collins, 1 August 1671, in E. G. Forbes, L. Murdin and F. Willmoth (eds.), *The correspondence of John Flamsteed, the first Astronomer Royal*, vol. 1: 1666–1682, Bristol: Institute of Physics Publishing, (1995), Letter 65.
[277] Beale to Hartlib, 18 January 1660. **BL** MS Add. 15948 f.93v.
[278] Gascoigne to Oughtred, in **Rigaud.** vol. 1, 35.
[279] **RGO** 1/44, Flamsteed's notebook, f.22r.
[280] Bernard to Collins, 3 April 1671, in **Rigaud.** vol. 1, 158.
[281] Flamsteed to Oldenburg, 19 April 1671, in E. G. Forbes, L. Murdin and F. Willmoth (eds.), *The correspondence of John Flamsteed, the first Astronomer Royal*, vol. 1: 1666–1682, Bristol: Institute of Physics Publishing, (1995), Letter 143.

English Catholics who found themselves in peril during the Civil War removed to the continent and returned later. Some travelled widely within the Low Countries, France and Italy. Though driven from England by virtue of their expressed politics and religion, their views do not seem to have impeded their friendships abroad. They corresponded with one another, and with Henry Oldenburg. For all the talk, little was accomplished. The non-spherical lens failed to open up fresh marvels of the heavens, and as the Royal Society's driving force waned, the London spectacle-makers were left with little more than a growing market for relatively cheap small and medium telescopes and microscopes. Most of the literature deals with improvements to the microscope, brought about by arrangements of structure, which do not shed any light on lens-grinding practices.

Flamsteed began taking a serious interest in astronomy whilst living in Derbyshire, from where he corresponded with Sir Jonas Moore, architect and surveyor, over the latter's purchase of lenses from Cock.[282] He recommended that Moore ask for two plano-convex glasses for a twelve-foot telescope, which when placed pole to pole would, he believed perform better than a single lens (though presumably costing more). However, when he tried the glasses he found them 'very indifferent', the front one the better of the two.[283]

John Yarwell

Figure 38: six-draw refracting telescope, by John Yarwell, English, late seventeenth century, © Whipple Museum, Cambridge, Wh.0876.

With the demise of Cock in 1696 came the rise of John Yarwell. The optician, Yarwell, had been apprenticed to Richard Edwards in the Spectacle-makers Company and on Edwards's death was turned over, first to Edwards' widow Mary

[282] Moore to Flamsteed, 10 October 1674. **RGO** 1/36 f.77; Flamsteed to Moore, 13 October 1674. f.29v.

[283] Flamsteed to Moore. **RGO** 1/36 f.45.

and then to Nicholas Shield. By 1671 he was working independently, recorded between 1672 and 1683 'at ye Archimedes and Spectacles in St. Paul's Churchyard'.[284] He rose to prominence in the trade, becoming master of the Spectacle-makers between 1684 and 1686 and again between 1693 and 1694.

Among others, Yarwell supplied Abraham Sharp, formerly Flamsteed's assistant at Greenwich Observatory, but latterly retired to his family home near Bradford. From this remote rural location, probably under clearer skies, Sharp continued assiduously to send his observations to Flamsteed, using instruments largely of his own making. The contents of Sharp's workshop are known only from the inventory of sale, made after his death. In addition to various mathematical instruments there were four telescopes, unvalued; a two-foot telescope, at two shillings and six pence; a double microscope, valued at one pound and ten shillings; sundry small perspectives, one in 'bow' at one shilling, one in 'brazil' at six pence, burning glasses and 'a box of telescope glasses'. There are no tools for lens grinding, and Sharp was obliged to rely on contacts with London opticians, Yarwell among them.

Yarwell's letters to Sharp reveal something of the craftsman's problems:

> [As] for the convex glass you desired to be of unrolerd glas that I never saw any glas but what had a color if you mean a whit glas they are all full of vanes and not fit for telescopes the glas I make for convex and all the rest of the trade are looking glass plate broke and we chuse that part which is free from vanes and bubles and as good color as can be gotten.[285]

A month later Yarwell was sending Sharp's order, with his invoice:

> Sir I have this day delivered the parsell as you desired ... you desire to know what a 6 foot glas with 6 glasses would cost the last I sould I had fifty shill for and cheape annuf of considring all I have sent them by Mr Adkins

for a 6 foot case all vellam & green & gilt drawers	1 : 0 : 0
for 16 foot obet glass	0 : 7 : 6
for a large convex	0 : 3 : 6
for 4 obet large	0 : 8 : 0
for 8 comon & 2 obet glas	0 :15: 0
for 2 cex of 3 inch half & 1 inch	0 : 1 : 6
for a pound of brass your cost	0 : 2 : 4
box cost	0 : 0 : 8
	2 :18: 6

[284] Adler Planetarium Webster Signature Database: http://historydb.adlerplanetarium.org/signatures/y.pl [accessed August 2016].
[285] Yarwell to Sharp, 22 July 1704. **WYRO** 16D86, Box 134, Bundle 22.

> I think I need say noe more I hope the glasses will spake for them selves and the prises lower than I should have sould if you had come hear.[286]

Yarwell continued to persuade Sharp that he was getting a cheaper price than others customers. In September and then again in October he wrote,

> I beg your pardon for sending the 12 feet obet glas by mistake I have maid one of 24 or better if it pleas if not return I have maid the rest good and have sent 2 obe glas draws 4 fot 10 inch which is longer than I sell that length by 3 inches & as you desire longer than 5 foot you will find 2 stand 5 foot 2 inches I sent them both that you may fitt with your mind return or alow as you please I think if the long obet glas is for yr purpose it is cheape att 10 sh: the rest as be for you
>
> | | |
> |---|---|
> | for a 24 foot ob.gl. | 0 :10: 0 |
> | for 3 convex large | 0 :10: 6 |
> | for 6 convex | 0 : 9 : 0 |
> | for 4 larg ob. 5 foot | 0 : 8 : 0 |
>
> before this comes to you I shall have 40 shill for an obet glas noe larger and but 5 foot longer & 45 sh for an eye glass.[287]
>
> Sir I have recd your letter for a parsell of glasses I am fitting of them & shall be done 14 days next coming the mony you sent I recd but for yr way of discounting the prise if they come not exactly to the size is what I never know before especially at such low prises, this what I would not doe if I was to spake it yourselfe and for not wrighting you word that I had recd this money I thought the carier would lett you know & thought I funded you the charge of a letter by it.[288]

Sharp's order was, it would appear, beyond Yarwell's normal business, and he had trouble getting glass thick enough to grind the curvatures Sharp desired. Yarwell's frustration is eloquent:

> Sir I am sorry I broke my promise that you had them noe sooner but this I doe faithfully assure you that in all my life I never had such a difficult parsell to make and I hope I never shall again Sir those glass are all out of the comon way and noe part of looking glass soe thick soe forth to work them up and if vanes lay them by for Burning glases or else I must worked them flatt and the vanes to be all lost I have as many as proved with vanes may be a long time to

[286] Yarwell to Sharp, 20 August 1704. **WYRO** 16D86, Box 134, Bundle 22.
[287] Yarwell to Sharp, 9 September 1704. **WYRO** 16D86, Box 134, Bundle 22.
[288] Yarwell to Sharp, 20 October 1704. **WYRO** 16D86, Box 134, Bundle 22.

> sell much more I could say to yourself but my talent doth not lie in wrighting and which I never loved. but I hope by these you know soe well what troubell is required in making all those odd lengths the 12 large are full as much work as the large ones you had before if I may be believed for the other 10 convex you know the prise for the 4 obet I throw the m.. for .. & at last I send them all for you to make the prise and that shall content me and ware it not more to oblige you that I have a grate respect for than the profit I would never make such a parsell I cannot express the trouble for the for the lens cost me 16:6pence without my work it is very good in all the parts and I hope you will think it very cheape at 20 five shill for the glases you wright for now & the answer to your letter shall be done with all convenient time but I am making a grate parsell for the Indies & shall aske the more time and hope to hear of your good liking of those I have sent if not you know I would always make it my indevor to please you.[289]

The last, desperate letter of this series, further illuminates Yarwell's troubles:

> I am glad you omit the large convex glases for I allways lost by them for the other sort I have mislaid your letter and know not what they are which you most want if you please to send me a not of them I will doe them with all the speed I can I wood not tell you a gane that thick glas without vanes or sands is hard to gett and I must tell you that the way of working all our convex glasses now is quite another way than formerly for now all the way of making them is by working 4 6 or eight to gether and our tubes is now fitted for this way soe you may know that your sending for soe many several depts gives me not only a grate deal of troubele and the rest are not fitt for my purpose you may believe I should be glad to please both you and all men but I must confess I have had more complaints from you than from all the rest of mankind and yours the most or severall months with the least profit for the last you had which I recd one pound for the journeymans wages cost me thirty shill for you may sure I shall gett no estate by them and yett if your friend had not perswaded me much to give you this letter I believe I should have bene silent soe much I prefer the playing my friends before my own interest for after all you can find no fault in the work of the glases but the glas itself which you may be sure I should gett as good as possible I can tho not soe good som times as I could wish I hope you will excuse this long letter which I take noe grat pleasure in wrighting nor you in reading but as you are my friend I would sett the matter in albright light and leave the rest to yr better judgement.[290]

[289] Yarwell to Sharp, 25 November 1704. **WYRO** 16D86, Box 134, Bundle 22.
[290] Yarwell to Sharp, April 1705. **WYRO** 16D86, Box 134, Bundle 22

Three lenses were found amongst this correspondence, presumably sent by Yarwell. On analysis their chemical composition resembled that of Venetian crystal, making it probable that they were ground from old mirror glass.[291]

Advertising and the telescope market

Observatories active during the seventeenth century and prior to the introduction of the achromatic lens may have been generally equipped with telescopes and positional instruments, but the *Greenwich list of observatories* does not yield much in the way of information about the optical parts of such apparatus.[292] The purpose of Greenwich and other national observatories was primarily the compilation of star tables, for the use of navigators. The brightest stars, those easily observed by seamen, were followed. The astronomers were less concerned to search for minor satellites, comets and double stars, which remained the province of private observers. In any case, much apparatus has vanished, some destroyed when fire swept through these buildings, more discarded as obsolete or cannibalised for other uses. Leonardo Ximenes, astronomer, mechanic, naturalist, and teacher of physics at the Jesuit college in Florence, enjoyed a wide range of correspondents. It may have been from one such colleague that he acquired his telescope by John Yarwell.[293]

The earliest known instrument with a lens signed by a London maker is the objective of a telescopic level, signed 'Christopher Cock 1668', now in the Whipple Museum. A later example is in a passage instrument by Jonathan Sisson, its lens signed 'Mann fecit 1739' referring to the instrument maker James Mann, of Ludgate street London, and supplied to Bologna Observatory.[294] Mann advertised in *The London Gazette,* 3 May 1697:

> At the sign of the Spectacles in Butcher-Ball Lane, near Christ Church, London, liveth James Mann, who maketh and selleth all sorts of spectacles, prospective glasses, telescopes, reading glasses, burning glasses, magnifying and multiplying glasses.

We know from evidence in newspapers and from books and other documents that a thriving community of opticians was active in London, certainly advertising all

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[291] I am grateful to Robert Anderson, then Director of the British Museum, for encouraging Ian Freestone of the British Museum's Department of Scientific Research to undertake these analyses, and to the owners of the Sharp material for permission.
[292] H. D. Howse, 'The Greenwich list of observatories', *Journal for the history of astronomy*, 17, (1986), i–iv and 1–100.
[293] C. Triarco, 'La specola di Leonardo Ximenes a Firenze e la catalogazione dei suoi strumenti', in L. Pigatto (ed.), *Giovanni Toaldo e il suo tempo: Nel bicentenario della morte: Scienze e lumi tra Veneto e Europa*, Cittadella: Bertoncello, (2000), 381–409.
[294] Inventory MdS 122.

manner of apparatus, and probably providing the lenses for many instruments manufactured or retailed by other equally famous names.

Shop signs depicting spectacles were not the sole preserve of those who made these items. They decorated such inns as the 'Bull and Spectacles' and a toy-shop in the Strand, which in 1731 bore the sign of the 'Great Golden Spectacles'. Both the original arms of the Spectaclemakers' Company, 'argent, three pairs of spectacles vert, garnished or' and its replacement in 1739 by a more complex design which included two pairs of spectacles, inspired the signboards of opticians. Given the simple outline and immediate recognition of spectacles, it is not surprising that these, rather than telescopes, were their recognised symbol. Telescopes and microscopes figure on the trade cards and newspaper advertisements that proliferate from the late seventeenth century. In the eastern parts of the City, where maritime interests held sway, octants and quadrants became popular signs in the eighteenth century.

John Houghton, Fellow of the Royal Society and an apothecary, was based in the commercial heart of London and moved in mercantile and banking circles. Over the years he expanded his wares to include such exotic products as brimstone and sago, alongside spectacles and telescopes. He was recruited to the Royal Society's agricultural committee and this inspired him to issue two series of letters, the second of which, *A collection for the improvement of husbandry and trade*, was published weekly between 1692 and 1703. Beginning on 4 August 1693 Houghton dealt with glass and optical products, writing

> Whereas generally the spectacles that are made and sold in England are irregular because the tools they are made with are so; now there is found out a new way of making the best sort of spectacles that are true sections of spheres as cheap as the best irregular ones used to be sold for. I have enquired of those who are extraordinarily skilled in optics, who confirm the same, and think they deserve to be encouraged. These are to be sold by John Marshall at the sign of the Archimedes and Spectacles in Ludgate Street, London.

By October Houghton was adding that Marshall 'hath also invented a large double microscope, a pocket microscope, and a wheel perspective glass, with 3 concaves in the eye glass, fit for all weathers. These are more useful than any yet have been.'[295]

Marshall had been an apprentice of Jack Dunning, a turner, and was not a member

[295] J. Houghton, *A Collection for the improvement of husbandry and trade*, London, (1692–8), vol. 3, nos. 53 and 63.

of the Spectaclemakers' Company though he made microscopes for Boyle and served as 'Optician to his Majesty.' The 'new way', referred to by Houghton and promoted by Marshall as his own invention, consisted of grinding several lenses at the same time, within a brass basin or former, in place of the iron one used by 'common spectaclemakers'. Robert Hooke met Marshall in 1688 and was impressed by his skill at glass grinding and making large aperture lenses.[296] This relationship encouraged Marshall to attend at the Royal Society in November 1693 and to seek their declared approval of his new method. Hooke and the astronomer Edmund Halley were ordered to examine Marshall's method of grinding, and to report back to the Society. Halley had spent six weeks with Hevelius in Danzig, and had in any case himself outlined to the Society his design for a machine to grind long-focus lenses, though, like so many other designs it seems never to have made the jump from imagination to reality. On receipt of a favourable report, the Society had been minded to supply Marshall with a certificate, but on second thoughts they decided that a letter would suffice, and this letter was duly written on 15 January 1693/4.

Marshall's claim that his method was new cannot be upheld. Beeckman and his contemporaries referred to brass basins; iron may, however, have been the choice of common spectacle-makers because of its cheapness, and because of the variable composition and quality of English brass at that time. Nor was the technique of polishing several lenses together entirely novel, having been practised, possibly by Drebbel, in London, and probably by Hevelius and Hartsoeker. Secretary to the Royal Society, Richard Waller, in his preface to Hooke's *Posthumous works* (1705) wrote:

> I remember Mr Marshall when he desired the Society's approbation of his new method of grinding spectacles and other optick-glasses, owned that he had the first intimation of it from a hint of Mr Hooke's in his book about the polishing of many very small microscope object-glasses at once.

It should therefore have come as no surprise that the Spectaclemakers Company supported the objections of its members that the method was not new and that the testimonial ought to be withdrawn, though it was perhaps odd that this objection was not raised for some months. Much hot air and paper was exchanged before the matter was dropped, leaving the outcome unclear. Marshall's claim and the subsequent counter-claims were sustained for some time in the press, and these arguments provide an indication of techniques practised at the time by those leading opticians who, in addition to spectacles, reading glasses and burning glasses, were also making telescopes and microscopes.

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[296] I have drawn on D.J. Bryden and D.L. Simms, 'Spectacles improved to perfection and approved of by the Royal Society', *Annals of science*, 50, (1993), 1–32, for much of the background to Marshall's claim.

John Yarwell also joined in the advertising war. His trade cards borrow the well-known image of the astronomer and instrument maker Johannes Hevelius seated at his telescope. To this familiar scene Yarwell added as many of his instruments as could be fitted in, adding, perhaps helped with spelling,

> All the above instruments as telescopes of all lengths, microscopes single and double, perspectives great and small, reading glasses of all sizes, magnifying glasses, multiplying glasses, triangular prisms, speaking trumpets, spectacles fitted to all ages, and all other sorts of glasses, both concave and convex.[297]

Advertising in this period was certainly vociferous and much given to exaggeration.[298] Partners George Willdey and Timothy Brandreth, trading at the sign of the Archimedes and Globe, put a lengthy notice in the *Daily Courant* of 24 March 1707 claiming that they had a microscope which magnified an object more than two million times, and a concave metal, that is, a concave metal mirror, that united the sunbeams so vigorously that in a minute's time it melted steel and vitrified the hardest substance. They continued

> Also we do protest we pretend to no impossibilities, and that we scorn to impose on any gentlemen or others, but what we make and sell shall be really good[…] spectacles by which objects might be discovered at twenty or thirty miles' distance, modestly speaking[…]
>
> [W]e are now writing a small treatise with the aid of the learned that gives the reasons why they do so, which will be given gratis to our customers.

Yarwell and his partner Ralph Sterrop took exception to this boast by their former apprentices Willdey and Brandreth. They gave vent to their annoyance in the *Daily Courant* of 16 April:

> By John Yarwell and Ralph Sterrop, Right spectacles, reading and other optic glasses, etc., were first brought to perfection by our own proper art, and neede not the boasted industry of our two apprentices to recommend them to the world; who by fraudently appropriating to themselves what they never did, and obstinately pretending to what they never can perform, can have no other end in view than to astonish the ignorant, impose on the credulous, and amuse the public. For which reason, and at the request of several gentlemen already imposed on, as also to prevent such further abuses as may arise from

297 Several prints of this card survive. The example in the British Museum Prints and Drawings Collection is Banks Y.5.310.

298 For more examples of newspaper advertising, see Alexi Baker, *This ingenious business: The socioeconomics of the scientific instrument trade in London, 1700–1750*. Oxford University, D.Phil thesis, (2010).

> the repeated advertisements of these two wonderful persons, we John Yarwell and Ralph Sterrop do give public notice, that to any person who shall think it worth his while to make the experiment, we will demonstrate in a minute's time, the insufficiency of the instrument and the vanity of the workmen by comparing their miraculous Two-Foot with our Three and Four Foot Telescopes. And therefore, till such a telescope be made, as shall come up to the character of these unparalleled performers, we must declare it to be a very impossible thing.

At a time when makers of microscopes and telescopes were seeking more customers, the last thing they wanted was for wealthy men to have been fooled by false claims, as this was likely to put off others who were considering an optical purchase. For the ignorant, *caveat emptor* was not enough to save them a waste of money.

Willdey and Brandreth against Yarwell and Sterrop continued in this vein for several weeks until on 1 May 1707 the younger men made the mistake of bringing John Marshall into the story, claiming that neither Yarwell and Sterrop, nor Marshall, could make a better telescope than they could. This roused Marshall's anger and on 8 May he reminded readers of his Royal Society approbation, adding

> I have made spectacles, telescopes and microscopes for all the Kings and Princes courts in Europe. And as for the 2 new spectacle makers, that would insinuate to the world that they were my best workmen for several years: the one I never employed, the other I found as I doubt not but many gentlemen have and will find them both, to be only boasters and not performers of what they advertise &c. &.

After two more outbursts, one from each side, the storm subsided. Whether the cost to both parties was worthwhile, we do not know.

<u>Handing down craft skills</u>

Craft skills were usually learnt in a period of apprenticeship, followed sometimes by journeyman work. The documentation that bound apprentices to a master has survived well enough for many long chains to be seen. While seven years was the usual servitude, longer periods are known. When Shield sought his freedom of the City of London in 1647, it was on the grounds that

> [he had already] served fourteen years with several freemen to spectaclemaking and marrying before the expiry of his indenture desires his freedom of the city and redemption to Spectaclemakers Company with payment.

This was granted, friends and relations standing surety for him.[299] Shield went on to become Master of the Spectaclemakers, which did not stop him having his shop searched on 20 April 1668, when 'Nicholas Shield, as Master, and the Wardens of the Spectaclemakers visited Shield's house in Fenchurch Street, finding him at work on eighteen pairs of spectacles made from looking glass shaped only on one side.' For this transgression, he was fined 20 s for each pair, amounting to the considerable sum of eighteen pounds. He refused to pay, and it was ordered that he should be, pursued at Common Law for this sum.[300] Interestingly, Yarwell was one of Shield's apprentices at this date.

Skills relied on tools and equipment, and some information on this subject can be gleaned from inventories and wills. The Spectaclemakers, along with other City of London guilds, assisted when one of their members died intestate, leaving orphans in need of support. In such cases, the contents of a man's shop, his debts and credits, were inventoried, and presumably sold to raise money for his dependents. Only two such inventories have survived, one for John Clarke, who died in June 1674, the other for Thomas Sterrop, who died in 1728.[301]

In John Clarke's inventory we find:

Wares in the shop and dining room:		
	22 glasses great and small	£83–0–0
	12 dozen of cards and sticks	3–0–0
	24 dozen of combs of various sorts	2–8–0
	24 dozen knives and forks	4–15–0
	22 dozen spectacles, burning glasses etc	2–17–0
	stands[…] table frames	2–2–0
In the shop and warehouse:		
	Comb boxes, powder boxes and a pile of whips	£17–0
	3 dozen leather cases and lumber	2–16–0
Ready money in the house		£120–0–0
Clarke owed:		
	To King for spectacle frames	£5–0–0
	Read, looking-glass frame maker	4–0–0
	Robinson, glass-seller, for filling and other things	2–10–0

[299] **CLRO**, Repertories of the Court of Aldermen, 8 April and 4 May 1647. Rep 58 part 2, on 92b and 96.
[300] **London:** MS 5213 Spectaclemakers Company Minutes, vol. 1.
[301] **CLRO**, Orphans' Inventories. John Clarke, 935 f.335; Thomas Sterrop 3285 f.123.

Thomas Sterrop had been Yarwell's partner and successor. His inventory, itemizing his domestic possessions room by room (not included here, apart from two beds and bedding, chairs and a table) discloses a small workshop, a remarkable quantity of optical goods, and a list of suppliers:

In the garrett: two beds and bedding, chairs and a table, working bench, polishing post and bell.

working tools valued at		£7–4–0
708 microscopes of different sorts		13–3–8
69 telescopes of different sorts		26–16–11
7 weather glasses		4–7–0
564 spectacles of various sorts		19–1–0
7 prisms		10–6
300 prospect cases fitted		19–1–6
8 pocket looking glasses		1–18–6
17 speculums		8–13–0
17 magnifying glasses		8–9
3 cameras		2–4–0
342 spectacle cases		11–16 –11½
80 reading glasses		13–7–6
792 prospect glasses in vellum, ivory, wood brass and bone		26–3–10
44 short sight glasses		2–0–0
846 tubes		5–18–3
348 watch glasses		14–0
384 burning glasses		2–16–1
1428 small concaves		2–9–9
23 sticks unfitted		5–5–6
2016 small object glasses		3–1–8
3 night object glasses		17–0
7 cane heads		1–0–0
magick lanthorn and pictures		1–13–0
One pair of barnocles (binoculars)		3–0
852 pairs of spectacles unsorted		7–9–6
216 spectacle frames		1–9–1½
150 white skins		3–15–0
22 things in the showcases valued at		1–5–0
	Total:	£324 –8–8

Sterrop held £200 South Sea annuity stock, had £3–3–0 cash in the house, and £137–1–0 owing to him. He owed money to:

Sworton or Sweeton	£9–15–0
[Matthew] Loft (Spectaclemaker)	4–19–0

Bush	4–4–0
Perkins	10–1
Day	1–5–0
Peirce	1–6–0
Pratt	14–0
[John] Phipps (Spectaclemaker)	5–0–0
Lerroux	7–0–0

Another slender source of information on craft practice comes from wills of spectacle-makers, made before they disposed of their equipment. Regrettably we only have the nun-cupative will of Reeve and for Shield a remonstration on the part of his wife.[302] But William Tucke of St Bride's parish, who died in 1697, left his apprentice Richard Clarke 'all my mills and working tools used in my trade'.[303] A connection between this Richard Clarke and the John Clarke mentioned above seems likely, but is unproven. The will of John Marshall, written in 1721, two years before he died, gives to his stepson Isaac Johnson 'those tools which were at the house of his sister Mrs Pomfret'. No spectacle-maker of this name is recorded, and possibly the Pomfret house merely offered workshop space. Marshall's son-in-law John Smith was to have 'all the tools that are in his shop or elsewhere'.[304] John Smith had been Marshall's apprentice and succeeded him. James Burton, an optical turner of Johnson's Court, Fleet Street, made his will shortly before his death in September or October 1778. All his estate and 'effects of whatever sort' were bequeathed to opticians, John Dollond and Henry Shuttleworth, 'to carry on the trade and business of optical turner for the benefit of Burton's four children', with the proviso that his son Henry might wish to take over the business when he reached twenty-one.[305] No spectacle-maker named Henry Burton is recorded.

<u>John and Peter Dollond</u>

The Dollond family rose above the numerous small opticians by virtue of the excellence of their large lenses, at a time when national observatories were buying independent large telescopes in addition to the positional instruments where the telescope was ancillary to the graduated arc. The family was of French Huguenot stock, having come to London in the aftermath of the revocation of the Edict of Nantes. John Dollond established himself as a silk weaver in Spitalfields, on the eastern margin of the City of London, and it was his son Peter who first practised as an optician, subsequently being joined in that trade by his father. Their story is dealt with in Chapter Eight.

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302 **Westminster Archives**, Westminster Wills, Act Book 6 f.57r and 64v.
303 **NA,** PROB 11/ 436 q.18. Will of William Tucke, written and executed in 1697.
304 **NA**, PROB 11/589 q.32.
305 **NA**, PROB 11/1046 f.75r. Will of James Burton, written 15 September 1778, proved 5 October 1778.

Chapter Eight
The achromatic lens in Europe

The natural philosopher Isaac Newton claimed to have begun grinding non-spherical optical glasses in 1666, when he acquired a glass prism to investigate the prismatic spectrum.[306] Of the six surviving prisms purporting to have belonged to Newton, three have recently had their refractive indexes measured.[307] One, in the British Museum, had a specific gravity of 3.36 and a refractive index of 1.55, which falls mid-way between the indexes deduced for the two glasses in Gascoigne's telescope of 1641.[308] Two prisms having a somewhat tenuous association with Newton are at the Whipple Museum of the History of Science in Cambridge; their refractive indexes are 1.5792 and 1.5805. Three prisms in the Museo Civico, Treviso, in Italy, formerly thought to have belonged to Newton, are now considered to be of Italian origin, made for an admirer of Newton, Count Francisco Algarotti, for his own experiments in the mid eighteenth century.

None of the above-mentioned prisms can be securely associated with Newton, who concluded from his experiments that no lens, whether spherical or non-spherical in figure, would be free from chromatic aberration. It appears, however, that Newton arrived at this conclusion from theoretical considerations before devising the experiments, involving glass prisms immersed in water-filled prisms, and this led to the results of his practical trials conflicting with theory. Another problem for the modern interpreter of Newton's notes on this matter is to know if by 'glass or crystal' Newton means two materials or is giving two words for one material. Even 'water' may not have been what it would seem, as the possibility exists that Newton may on occasion have added lead acetate. Nevertheless, it appears that Newton did endeavour to make a glass-water compound achromatic lens but found it ineffective.[309] Despite this ex-cathedra pronouncement, others continued to search for the elusive material or figure that would diminish the coloured bands which so hindered telescope users, and in particular astronomers. One such, the astronomer David Gregory, was the first to propose a composite lens comprising

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[306] Newton to Oldenburg, 6 February 1672, in H. W. Turnbull (ed.), *The correspondence of Isaac Newton,*vol. 1, (1959), letter 40.
[307] A. A. Mills, 'Newton's prisms and his experiments on the spectrum', *Notes and records of the Royal Society*, 36, (1981), 13–36.
[308] S. B. Gaythorpe, 'On a method for deducing approximately the focal length and magnifying powers of early telescopes', *Monthly notices of the Royal Astronomical Society*, 85, (1924–5), 659–662.
[309] A. E. Shapiro, 'Newton's "Achromatic" dispersion law: Theoretical background and experimental evidence', *Archive for the history of exact science*, 21, (1979), 91–128.

two materials differing in their refractive indexes. The inventor Tito Livio Burattini considered infilling two closely spaced lenses with distilled water in summer, and with spirit in winter.[310]

The achromatic lens in London[311]

When, a century or so later, the optician Peter Dollond explained to the members of the Royal Society how his father had succeeded where Newton had failed, he said,

> [...]it is well known that in Newton's time the English were not the most famous for making optical instruments. Telescopes, opera glasses etc were imported from Italy in great numbers, and particularly from Venice where they manufactured a kind of glass much more proper to optical purposes than any made in England at that time. The glass made at Venice was nearly of the same refractive quality as our own crown glass, but of a much better colour, being sufficiently clear and transparent for the purpose of prisms. It was probably with this kind of glass that Newton's prisms were made, and it appears to be the more so, because he mentions the specific gravity of common glass to be to water as 2.58 to 1 (Newton's *Optics* (1704), 247) which nearly answers to the specific gravity we find the Venetian glass generally to be of. Having a very thick plate of this glass which was presented to me about 25 years ago by Professor [Jean-Nicolas-Sébastien] Allamand of Leyden, and which he then informed me had been made many years, I cut a piece from this plate of glass to form a prism, which I conceived would be similar to those made use of by Newton himself. I have tried the Newtonian experiment with this prism, and find it to answer so nearly to what Newton relates, that the difference which remains may very easily be supposed to arrive from any little difference, which may and does often happen in the same kind of glass made at the same place at different times. Now the glass prism made use of by Dollond [that is, his father John Dollond], to try the same experiment in the year 1757, was made of English flint glass, the specific gravity of which I have never known to be less than 3.22. This difference in the densities of the prisms, used by Newton and Dollond, was sufficient to cause all the difference, which appeared to the two experimenters in trying the same experiment. From this it appears that Newton was accurate in this experiment, as in all others, and that his not

[310] Instructions accompanying lenses sent to Cardinal de Medici. Florence: Biblioteca Nazionale, MS Galileo. In a previous letter Burattini had mentioned double glass and liquid lenses.

[311] For a fuller account of this episode see B. Gee (edited by A. McConnell and A. D. Morrison-Low), *Francis Watkins and the Dollond telescope patent controversy,* Farnham: Ashgate, (2014).

> having discovered that, which was discovered by Dollond so many years afterwards, was owing entirely to accident; for if his prism had been made of glass of a greater or less density he would certainly have then made the discovery, and refracting telescopes would not have remained so long in their original imperfect state.[312]

Despite what Peter Dollond would have his contemporaries believe, the achromatic lens had not been created *ex nihilo* by his father and John Dollond's patent of 19 April 1758 was later contested by the London opticians who had been making such lenses for about twenty years. Progress had been made in calculating the density and figures of the two differing media, which would be needed for such a lens, this work having been done by mathematicians Leonhard Euler and Samuel Klingenstierna in Germany and Sweden respectively. Euler found himself unable to put his theory to the test for want of a heavier medium of the correct refractive index.

While the astronomer and mathematician Johannes Kepler, and many others since, examined the lens of human or animal eyes when considering achromatic vision, in the 1730s the first practical achromatic telescope was made by order of a man with no apparent connections with science or medicine. This man was Chester Moor Hall, a practising barrister of the Inner Temple and a minor landowner in Essex. He is not known to have belonged to any of the learned or polite societies, nor have any of his letters or papers been traced. On his monument in Sutton church in Essex he is described as 'an able mathematician' and his only known work is a small table 'to show the daily increase in any sum &c.' intended to assist with calculating the rent of chambers in the Inner Temple.[313] What roused his interest in the subject of optics is unknown; it is possible that he attended some of the scientific lecturers being delivered in London. Presumably he did not accept Isaac Newton's assertion that the achromatic lens was an impossibility, and from experiments reached the broadly correct conclusion that a compound lens made of two types of glass of differing refractive index would correct this chromatism and throw an image largely free from spurious colours.

By 1733 he had approached London opticians, Edward Scarlett and James Mann, requesting from one a convex lens of crown glass, and from the other a concave lens of dense lead crystal. It so happened that both opticians contracted the job to the glass-grinder George Bass of Fleet Ditch, who, realising that he had been asked to make two lenses which perfectly fitted together, and gave a colourless image, discovered that the buyer was Chester Moor Hall. According to the instrument

312 'Peter Dollond's account ... '. **RS.** L & P IX.131, March–July 1789.

313 See the *Calendar of Inner Temple records* where this document is listed in *Records of Inner Temple*, vol. 26, No. 86, 19 January 1771, Printed table of 20 ff. The date of 1771 is likely to refer to its acquisition in the records since by that time Hall was close to death.

maker Jesse Ramsden, it had been the optician James Ayscough who regaled John Dollond with an account of a marvellous telecope in his possession around 1755–6,[314] though Robert Rew who worked for Watkins, was later put forward as the informant (see below).

News of this invention passed to some of the London opticians who thereupon commenced to construct such lenses. Hall, however, remained silent during those early years, though he was alerted to events by Bass and visited John Dollond in 1758 when the latter was applying for a patent. Perhaps recognising that he in fact was not the true 'inventor', Dollond allowed the craftsmen making such lenses to continue until, after John Dollond's death, his son Peter Dollond commenced to prosecute those who were infringing the patent. Peter Dollond's first case was filed in 1763 against the partners Francis Watkins and Addison Smith. It was held under Lord Mansfield in King's Bench. Both were accused of 'trespass', namely making lenses in contravention of the patent. Their argument that the patent was not valid was dismissed, opening the way for cases against those other opticians making achromatic lenses for infringement of the Dollond patent.

In 1764 the Spectaclemakers Company got up a petition, addressed to the King as the nominal granter of patents, declaring that,

> [John Dollond] had permitted them to Enjoy the benefit thereof in Common with himself rather than Risque a Contest with them in relation thereto which might Probably Terminate in bringing a Public Discredit on his Patent and Eventually Issue in a Forfeiture or Avoidance of the same. But since the Death of the said John Dollond Peter Dollond his Son and Administrator (under Colour of the said Patent) hath Threatened to bring Actions against your Petitioners and any others of the Trade who shall make and sell the said Glasses. Whereby your Petitioners are Intimidated from carrying their Lawful Trades ... and the said Peter Dollond is now Attempting to Establish a Monopoly of the said Glasses for his own sole Benefit by Virtue or Colour of the said Exclusive Grant.[315]

Thirty-three opticians signed, including George Bass and Robert Rew, the latter identified as he 'who in the year 1755 Inform'd Mr John Dollond of the Construction of this Compound object glass'.[316] The petition was delivered to the

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[314] J. Ramsden, 'Some observations on the invention of achromatic telescopes by J. Ramsden FRS', **RS.** L & P IX.138.
[315] **NA.**, PRO PC 1/7, bundle 37.
[316] William Eastland, George Ribright, James Champneys (or Champness), John Eglington, David Deane, Benjamin Martin, John Bennett, John Troughton, Nathaniel Hill, John Cuff, Joshua Bostock, Samuel Wright, James Jameson, Joseph Hitch, John Cox, Peter Eglington, William Cole, Francis Morgan, John Cleare, John …. In order of signing, the names are: John

Attorney General in June 1764, but due to political upheaval, which resulted in the removal of the Attorney-General from office, it made no further progress and no judgement was ever pronounced on it. Probably no significance is to be read into the order of petitioners' names; the workshops of the opticians concerned were distributed along the elegant principal streets as well as the back alleys and courts of the Cities of London and Westminster, and the humble lanes of Clerkenwell.

A later case against James Champneys was heard before Lord Camden in the Court of Common Pleas, judgement being given in February 1766, with the memorable phrase which is now enshrined in patent law, that, 'it was not the person who locked up his invention in his scrutoire that ought to profit by such an invention, but he who brought it forth for the benefit of the public.'[317] From brief notices of Champneys' trial in the local press, we learn that Dollond was awarded damages of (according to differing reports) either £204 or £250. Finding this considerable sum may have contributed to Champneys' bankruptcy in January 1772. Two years later Dollond laid another claim, this time against Henry Pyefinch: nothing is known of the outcome, affidavits alone having survived.[318]

In answer to Ramsden's objections to his address to the Society concerning his father's work on the achromatic lens, Peter Dollond gave a somewhat different version of events. He explained that opticians had recently begun to use crown glass in place of the plate glass generally employed for objectives, when John Dollond called on Bass to purchase a reading glass, which Bass made in some quantity. He chose one of crown glass, because it was less tinted than those of plate glass, but Bass recommended the plate glass as throwing less colour round the image. John Dollond was at this time experimenting with various types of glass and he had brought these experiments to a satisfactory conclusion before patenting the new lens. There had never been any mention of a compound lens having previously been made by Bass or any other London opticians. Bass, however, wrote to Hall, who called at the Dollond shop on his next visit to London, and said that he had tried such experiments, but being too occupied with his legal affairs, had laid the idea aside and was happy to see that it was now being promoted.[319]

Bird, Tycho Wing, Samuel Scatcliff, Joseph Linnell, Burton, George Bass, David Drakeford, John Cooke, Robert Featley, Robert Rew, William Ford, John Davies, John Clack.

[317] *Gentleman's Magazine*, 36, (8 Feb. 1766), 102. This quaint expression is often erroneously attributed to Mansfield; it was repeatedly cited in later Patent Law disputes.

[318] **NA.** C 33/423(2), 460, Court of Common Pleas, affidavits, filed under `Dollond', Easter Term, 6 Geo.III, and Michaelmas Term, 8 Geo.III; **London** MS 14,805/1. Mrs Martha Ayscough of Ludgate Street entered into a bond with Dollond not to make refracting telescopes, witnessed by George Bass and Thomas Whitford, 30 June 1764. The document is endorsed 'This paper was shown to Whitford at the time of the Pyefinch v Dollond Chancery suit'.

[319] P. Dollond, 'Answer to a paper ...', **RS.** MS L & P IX.146.

It seems that Hall was present for at least one of the court hearings, but he was not called. Hall had resided, unmarried, at New Hall, Sutton, Essex, where he died on 17 March 1771, his legal heir being his older spinster sister Martha.[320] Once the London opticians became aware of Hall's invention telescopes fitted with achromatic lenses were sold for use at home and overseas.[321] When Dollond's achromatic telescopes were acquired by the Paris Observatory there was an immediate attempt to manufacture such lenses in France, but this was easier said than done, for although there was no problem in making clear crown glass, French glass-makers found it difficult to produce a batch of lead crystal which was homogenous throughout the pot and free from striations and patches of cloudiness.

The achromatic lens in Europe

Alexis-Claude Clairaut, writing to his fellow mathematician and physicist, Daniel Bernoulli, in 1761,[322] explained that Dollond had known of Euler's endeavours to correct chromatism by employing lenses of two different materials such as glass and water. The substance of his paper to the Berlin Academy of Sciences in 1747 would, said Clairaut, have enabled such lenses to have been constructed, had Euler been less attracted to theory and calculation than to practicality. In Paris the mathematician Pierre-Louis-Moreau de Maupertuis had an example of Euler's proposed object glass constructed of glass and water. However, the difference of dispersion between common glass and water was poorly understood and the composite lens proved unsuccessful, lacking the strong curvature needed to remove chromatic aberration induced a strong spherical aberration. Dollond had built on Euler's ideas by experimenting, not with glass and water, but with two different kinds of glass, which, though similar in their mean refractive indexes, differed considerably in the band between red and violet. Dollond constructed a lens from these two media, figuring the denser glass as a concave and matching it to a convex of the lighter glass, the whole comprising an objective of longer focus in which the rays of the various colours were reunited as Euler had proposed, and indeed, as Hall had achieved. This compound lens seemed to Clairaut to be capable of further improvement to diminish spherical aberration.

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[320] His library was sold by auction in London in 1772 but his books were not distinguished from those of another scientific library, some 6000 books being offered in the one sale.
[321] Anders Celsius acquired for Uppsala Observatory a thirty-six foot achromatic telescope 'with glasses according to the formula of Klingenstierna' by 1742, according to Per Collinder, *Swedish astronomers 1477–1900*, Uppsala: Universitetet (1970), 31, but Olov Amelin (personal communication 1995), assures me that this date is incorrect and no achromatic telescope was acquired so early.
[322] Clairaut to Bernoulli, 1 June 1761, in B. Boncompagni, 'Intorno alle lettere edite ed inedite di Alessio Claudio Clairaut', *Atti dell'Accademia Pontificia de' Nuovi Lincei*, 43, (1889–90), 263–4.

Clairaut then undertook several experiments, preparing a triple lens comprising a central English lead-crystal convex, having a refractive index of 1.6, flanked by a plano-convex and a biconvex lens, both of common glass.[323] He followed this by 'observations on the manner of working compound lenses'; the English crystal, he had been told, was made of three parts of white sand, three parts of cullet, one part of minium (lead oxide) and two of refined nitre. The material to be worked must be carefully selected, discarding any with flaws. The glass blanks should have their surfaces planed and be turned to exactly the same diameter, so that their centres would correspond. Two matching forms were called for, one to grind, the other to polish; when shaping the glasses one should have to hand the small calipers used by watch makers to test the thickness of the glass. The lens was then glued to a handle, and glass and form were both rotated, with tripoli or other powder as the polishing agent. The glasses must then be secured in a cell of copper, and a ring of paper interposed to prevent the glasses from touching.

Clairaut's letter of 1 January 1762 discloses that he was employing a well-known Parisian optician, Georges (or George), who had the leading craftsmen working for him.[324] Nevertheless he and Georges did not agree about the best way to proceed, and Clairaut also found himself forced to wait his turn for Georges' attention. By August 1762 Clairaut was obliged to write that he could not meet Bernoulli's request for prisms of English crystal, the glass having become so scarce that French opticians were unwilling to part with the small amount they were holding. His craftsman Georges had the largest stock, and was using it to make some excellent telescopes, but Clairaut was even more pleased with those made by de L'Estaing, who was not a tradesman. Anyway, he had now discovered a substitute for English crystal: this was strass, the material used by lapidaries to make imitation gemstones. As it came from Germany, it was perhaps more readily available to Bernoulli. It had a density of 4.0 and possessed a high brilliance but was so soft that it was easily scratched, even by other glass. Clairaut had already prepared a compound lens with the convex lens made of strass, and it was very successful.[325] He seems to have been unaware that at the time of his letter, the creator of strass was already established in Paris. Georges Fédéric Straswas born in Wolfisheim near Strasburg. In 1714 he was apprenticed to a goldsmith in Strasburg. He then travelled around as a journeyman, before joining the widow of a Parisian jeweller named Prévost, in 1733. The following year he was trading under his own name and mark from the Quai des Orfèvres. The term 'stras' or 'strass' for

[323] Clairaut to Bernoulli, 1 June 1761, in *ibid.*, 265–8.

[324] Georges, or George, (no first name or dates available) was 'Lunetier du Roi' and 'Opticien de Mrs de l'acad des sciences'. He was established at Quai de Conti by 1772. See M. Daumas, (trans. M. Holbrook), *Scientific instruments of the seventeenth and eighteenth centuries and their makers*, London: Batsford, (1972), 267.

[325] Clairaut to Bernoulli, 4 August 1762, in B. Boncompagni, 'Intorno alle lettere edite ed inedite di Alessio Claudio Clairaut', *Atti dell'Accademia Pontificia de' Nuovi Lincei*, 43, (1889–90), 272–3.

this material appears in the *Dictionnaire de l'Académie Française* (1740). Such artificial precious stones had been made previously but Stras improved them. In his later years he made only artificial stones.[326]

Stras has been confused with others of a similar name. *The Oxford English dictionary* and *The encyclopaedia Britannica* have attributed the material strass to Joseph Strasser. There was also a goldsmith of Vienna named Strasser, to whom it is credited. The *biographisches lexicon von Würzbach*, published in Vienna in 1875, relates that this Strasser came to London and married the daughter of the famous Dollond. Modern research has, however, failed to identify this man, and historian Gabriele Greindl rightly suspects he may be a figment of the imagination.

In 1766 the Academy of Sciences offered a prize for a dense glass of optical quality but this was not taken up for many years. The astronomer Alexis Marie Rochon carried out many experiments with rock crystal and with liquid lenses, presumably to obviate the need for flint glass. In 1798 he wrote,

> When I undertook a journey to London, by order of Government, for the benefit of the sciences, I employed myself in a particular manner in the improvement of flint glass; and I was convinced that the properest and simplist means for rendering flint glass fit for constructing large achromatic telescopes consist in removing the threads by means of a glass-cutter's wheel. When these faults are removed, the glass is to be kneaded in an oven and under a muffle, in such a manner as to give it almost the form and size of the object-glass required to be made.[327]

Rochon explained that this process was amply described in his *Receuil de memoires sur la mechanique et la physique* (1783).

The way in which the glass tax was imposed (see Chapter Two) led to a recurrent dearth of optical-quality flint glass. In March 1775 Portuguese natural philosopher John Hyacinthe de Magellan conveyed to Swiss astronomer Jacques-André Mallet in Geneva, Dollond's inability to make any telescopes at the present time, since he lacked good flint glass, and if by chance a good pot of glass was come by, this would cost £100.[328] Magellan thought this probably the reason for Dollond having recently raised the prices of his telescopes. The situation was unchanged in September and October, though by February 1776 Dollond seems to have been able to produce a telescope for Mallet which met with Magellan's approval.[329]

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[326] G. Greindl, *Strass: Modeschmuck aus 2 jahrhunderten*, Munich: Heyne, (1990), 20.
[327] A.-M. de Rochon, 'Observations on platina &c., ... ', *Philosophical magazine*, 2, (1798), 175–6.
[328] At Apsley Pellatt's Blackfriars flint glass works, each pot held about 16cwt of fused glass.
[329] J. H. Magellan to J.-A .Mallet, Paris, 31 March 1775; London, 1 September 1775; London,

In March 1787 the German diplomat and passionate amateur astronomer Hans Moritz von Brühl was writing to Barnaba Oriani an astronomer at Brera Observatory, Milan, to express the hope that Herschel's telescope would prove successful, and that he hoped still more that Ramsden would be able to find a piece of glass perfect enough to make a twelve-inch objective.[330] The Blackfriars glassmaker Apsley Pellatt wrote in 1849 that,

> For many years subsequent to the time of Dollond English flint glass was almost the only heavy glass used for telescopes at home and on the continent. It was generally flint plus 10% extra lead, s.g. 3.250 to 3.350. Common flint glass, s.g. 3.200, consisted of: carbonate of potash - 1cwt; red lead - 2cwt; washed and burnt sand - 3cwt; saltpetre - 14 to 28 lbs; manganese oxide - 4 to 12 oz. It was sold to opticians in the form of annealed plates, 14 x 10 inches x ½ inch thick. Working a large pot of optical glass retarded glasshouse operations. In any pot the proportion of usable glass was small and the unusable glass was no good for anything else.[331]

In other words, while it was technically possible to adjust the temperature of the furnace to handle a large pot of optical glass, it was not a profitable business.

French glassworker Alexandre Tournant may have been responsible for sustaining a slender line of communication between England and France. In around 1771 the industrialist Matthew Boulton employed Tournant as a turner and maker of brass instruments. He is probably the workman referred to in a letter from Scottish physician and Lunar Society founder William Small, to the inventor James Watt at Glasgow, '[...]Mr Boulton has got a workman who makes achromatic glasses better than Dollond. He is a French man[...]'.[332] In October Small wrote, 'Boulton's operator does not make telescopes for sale. He works with Mr B as an elegant turner chasser &c &c &c so that I cannot provide you with a telescope.'[333] If Tournant's telescopes were not for individual sale, the man himself was apparently dispensable. In 1770 the Duke of Richmond had been enquiring after a good workman and, in December 1772, Boulton recommended Tournant, explaining that, among other skills, 'he[...] hath made for himself a very curious lathe he grinds optical glass very true & hath made some exceeding good achromatic Telescopes.'[334] The sentence being unpunctuated, it is unclear whether the 'curious lathe' served for grinding the glass. In a semi-literate French hand Tournant

13 October 1775. **Geneva BPU,** MS Supp. 1654, ff.25, 35, 40.

[330] H. M. von Brühl to B. Oriani, 25 March 1787, **Brera**, Scientific correspondence.

[331] A. Pellatt, *Curiosities of glassmaking*, London: D. Bogue, (1849), 41.

[332] Small to Watt, 3 February 1771, **Birmingham**, 340 (Small and family letters), 16.

[333] Small to Watt, 19 October 1771, **Birmingham**, 340.17.

[334] Draft, Boulton to the Duke of Richmond, 4 December 1772, **Birmingham,** Matthew Boulton Letterbook 136, 71.

requested Small disclose the exact composition of flint glass. He knew that manganese was used to correct the colour but he feared that it also diminished its transparency, and doubted that it was employed for London flint glass.

Tournant later returned to France and in April 1788 was one of several opticians elected to the body of engineers created by royal letters patent. This body, which included makers of various classes of scientific instruments, was set up to improve the low status of such craftsmen in France. Tournant was named 'engineer in optics to the king'. In 1789, apparently still deprived of lead glass, he wrote to Boulton asking him to buy the necessary flint glass from William Parker of Fleet Street, whose crystal was much in demand for chandeliers, lustres and, in lesser quantity, scientific glassware. In 1791 Tournant received a share in the annual awards made to the instrument makers. He had at some time worked in Berlin and held the title of optician to the Berlin Academy. In 1806, then 84 years of age, impoverished, and living in a charitable home at Chateau-Thierry, Tournant sought to sell to the French government his polishing machine. On investigation, it appeared that opticians did not use his machine—indeed it had never been made, the offer presumably being merely for a design.[335]

Within three years of the French Revolution there was a shortage of portable achromatic telescopes needed by the armed forces for reading telegraphs and other field use. The mathematician and astronomer Jean-Baptiste Joseph Delambre was asked to investigate and his report remarked on the persistent shortage of flint glass, which had obliged France to import either the glass or complete telescopes. The academy's prize had attracted no contenders, for the reward of 12,000 francs was considered inadequate in view of the expenses that would be incurred, given the slight chance of success.[336] However, he added, France's shortage was not caused by the rupture of commerce with England for that island was also experiencing a scarcity of glass, and he had seen a notice offering a prize of £1000 in the nautical almanacs for 1793–6, published in 1790. Delambre's report recommended considering the offer of one Fréminville to set up an optical shop with government assistance. Fréminville had obtained a substitute crystal—its not clear if this was rock crystal or strass—but his problem was also a shortage of workmen.

The house of Dollond was the principal source of high-quality telescope lenses during the last quarter of the eighteenth century, and it supplied lenses for instruments bearing the names of the most eminent makers, yet the compound achromatic lens did not entirely displace the simple crown glass lens. In May 1769 Bernoulli reported that John Bird polished his own lenses. Bernoulli asked Bird if

[335] **Arch. Nat.** F12 2435 file I/17.
[336] **Arch. Nat.** F12 2345, file I/7 Fréminville.

he fitted achromatic lenses to the telescopes of his mural quadrants; Bird replied that he did not: the larger diameter of such objectives would add significantly to the weight of the telescope, moreover it would take the centre of the axis of the telescope too far out of the plane of the arch.[337] In the autumn of 1771 Bird wrote to the astronomer Nathaniel Pigott, for whom he was then making a two-foot quadrant,

> You would have it in your power to observe stars of the 3rd magnitude; this I believe will be impossible, even with the Acromatic Glasses. Mr Professor Hornsby of Oxford has the Acromatic Glasses of about 3 feet focal length put to a Transit Instrument, in order to observe the Planet Mercury, but without success, for he has never been able to see him upon the meridian.[338]

In his next letter he reported,

> I have, since I wrote to you, consulted a Gentleman who has compared the Acromatic Glasses with the common: the comparison was at stars in daylight and he assures me, that the difference is inconsiderable.[...] I believe the best thing that can be done, will be to put 2 feet Telescopes* [in a footnote: * common glass] to an 18 inch Quadrant[…][339]

It appears that for larger instruments Bird also obtained his lenses from Dollond; Bird's contract for the Radcliffe Observatory instruments, and the associated correspondence, shows that the provision of lenses was negotiated directly with Dollond and that he supplied the estimate of their cost.[340]

<u>Scientific investigations into problems of flint-glass manufacture</u>

Although various prizes had been offered in France for a reliable method of flint glass manufacture, there was no success prior to the Revolution. In Italy the Venetian instrument-maker Domenico Selva actively sought to emulate Dollond's success, his achievements being reported by his son Lorenzo.[341] Selva obtained twenty pieces of flint glass but found only seven of these free from defects. He analysed the unusable pieces and arrived at an understanding of their composition. He would have liked to apply for the French prize but was unable to

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337 J. Bernoulli, London, 3 May 1769 (Lettre neuvième), in his *Lettres astronomiques*, Berlin, (1771), 126.
338 Bird to Pigott, 12 September 1771. **RAS**, Pigott letters, No.3.
339 Bird to Pigott, 28 October 1771. **RAS**, Pigott letters, No.4. Peter Dollond referred to what he regarded as Bird's abhorrence of achromatic lenses, **RS** MS, L & P IX.146.
340 Bird to Hornsby, 2, 9 and 16 February 1771. **Bodleian**, DD Radcliffe e.2, 36–40.
341 L. Selva, *Lettera di Lorenzo e Domenico Selva ottico pubblico as un suo amico sul ritrovato da lui fatto del Flintglass pei telescopi accromatici del Signor Dollond di Londra*, Venice, (1771). A number of Selva telescopes survive in public collections.

devote the time to this as he needed to support his family. Later, however, he was able to replicate the glass—better in quality than that of Dollond, as he claimed. Selva tells us that he had also read Robert Smith's *Optics* as translated by Pezenas.[342] He had made a telescope of three-feet focal length and one-inch aperture, which was tested at Padua against a similar instrument by Dollond. Selva's was found to be superior and it was this achievement that brought him the appointment of Venice's *ottico pubblico*.

At around the same time that Selva was attempting to make optical-quality flint glass, the famous Staffordshire potter and Royal Society Fellow, Josiah Wedgewood, was investigating the cause of the 'cords' and 'stratification' in a typical pot of glass. Wedgewood was accustomed to glaze his pottery with a thin slip or coating of lead glass. In 1776 James Keir, fellow member of the Royal Society of London and the Lunar Society of Birmingham, and proprietor of a glasshouse at Amblecote, near Stourbridge, suggested that Wedgewood might apply a frit containing the raw materials of flint glass, rather than one made from ground glass. In return for this advice Wedgewood decided to help Keir with his major problem, namely the spoilage of flint glass by streaks, veins and waviness, which rendered it useless for optical purposes. His findings were written up, perhaps for publication, but this did not happen and the text remained in manuscript.[343] It is undated but as it refers to Mr Wedgewood F.R.S., this fair copy must postdate his election in 1783. Here I summarise the relevant points of his investigations.

Wedgewood identified three 'orders' or grades of cords, those of the first grade gave the glass a fibrous appearance. Those of the second grade might be visible only by close inspection, or when the glass was cut and polished. Cords of the third grade gave the glass a wavy appearance, as when two liquids of different gravities, such as water and wine, were imperfectly mixed. He then considered the constituent parts of flint glass: a silica base, plus two very different fluxes, namely, lead, and potash, the latter generally containing a considerable proportion of marine and other neutral salts (soda). These heterogeneous materials might therefore be expected to produce glasses of different degrees of hardness, density, and fluidity; and Wedgewood presumed that these dissimilar glasses would tend to separate during fusion, according to their difference in fluidity, specific gravity, and perhaps some other causes at present not understood.

Wedgewood proffered evidence that this separation took place in the one pot of glass. Firstly, according to the workmen, the larger more prominent cords were

[342] Robert Smith's *Optics* (2 vols.) was published in 1738; the French translation by the Jesuit Esprit Pézenas was published in 1767.
[343] **Wedgwood.** A transcription is in R. E. Schofield, 'Josiah Wedgewood and the technology of glass manufacturing', *Technology and culture*, 3, (1962), 285–297.

harder to grind than the plain part of the glass. Secondly. In the molten glass, these cords were of a firmer or stiffer consistence than the plain part and therefore, in blowing, did not spread out so freely or so thin, leaving the surface of the vessel uneven and wreathed. In other words, they were less fusible, and in equal degrees of heat they were less fluid, than the plain part of the glass. Thirdly, the cords rose successively to the surface of the melting pot, in proportion to the thinness and maintenance of the fusion. They must therefore be lighter, with less specific gravity, than the glass through which they rose.

These observations not only showed that the substance of the cords differed from the rest of the glass, while at the same time indicating the nature of these differences. Wedgewood explained that it was well known that glasses made with the alkaline salts (potash) for a flux, were harder to cut or grind, were less fusible, and specifically lighter, than those made with lead; and as the cords were found to possess these characteristic properties of glasses, it followed, that they had more of the salts, and less of the lead, in their composition, than any other portion of glass in the pot. The glass-makers found that increasing the quantity of lead, also increased the cordiness, though Wedgewood was convinced that the lead could not add to the composition of the cords.

Having satisfied himself that the cords contained less lead than the rest of the glass; and as lead was known to give softness in proportion to its quantity, he concluded that the cords were harder than the rest of the melt, for the addition of lead added to the general gravity of the melt and thus stimulated the formation and uprising of the lighter threads. Wedgewood concluded that cords of the first order were unavoidably formed in the fusion of the heterogeneous compounds of which flint glass was made; that they were the hardest, the least fluid, and the lightest parts in the pot, or in other words, that they had the most salt or potash and the least lead in their composition. Regarding the second-order cords, he then considered the variations in any one pot of glass, which might be multiplied by adventitious causes, among which he pointed to the practice of collecting cullet from any source—mirrors, tableware, chandeliers etc.—which was then added to the new melt, so that the glass-maker could not exactly know the proportions of lead and potash in this new melt.

The workmen distinguished three kinds of glass in every pot, so dissimilar in colour and other qualities as to require being worked into three different kinds of ware. The top portion, which was full of large cords, was employed for common household goods; the middle part had the fewest imperfections, and was used for the finest ware, and it was from that part only, when it proved exceptionally fine, that some glass fit for optical working might be found. At the bottom was a softer species of glass, of a greener colour, which was worked into vials and other inferior articles. These layers were not distinct but graded imperceptibly from top to bottom. Wedgewood proved to himself that these differences in gravity and consequently in composition did occur, by having a portion of common flint glass taken out from the top of the pot at the time when the men began to work it, another specimen taken when they had worked it down a little way, a third when they had got to about the middle, and a fourth from near the bottom. He found their specific gravities to be as follows:

The top	3.266
The second, lower down	3.272
The third, or near the middle	3.274
Near the bottom	3.295

It appears that the trade was not generally aware of Wedgwood's findings and Schofield (in his ref. 36) suggests that the imposition of Excise duty made it unprofitable to experiment further. Perhaps Wedgwood was unwilling to admit his involvement publicly, well aware that the Excise had obliged others to terminate their investigations.

In 1808 Aimé-Gabriel d'Artigues, owner-manager of a glass-house at Vonêche, on the border of France and present-day Belgium, was invited to prepare a memoir, which was read at the Institut Nationale on 11 December 1809,[344] the result of investigations undertaken over the previous years. In his introductory 'Dissertation' d'Artigues stated, as the glass manufacturer Apsley Pellatt would later do, that the proprietors of glass-houses were reluctant to spend money on trials and experiments because sales of optical glass were relatively very small—not exceeding 500 kg for the whole of France—and its manufacture disrupted the normal business of the glasshouse.

The first to attempt to satisfy the opticians had been Defougeray, proprietor of the crystal glasshouse at Le Creusot (literally, 'The Crucible'), but he mistakenly supposed that adding more lead would produce optical-quality glass. This, as Wedgwood indicated, was a popular misconception. Despite government assistance Defougeray was only able to extract small pieces free of blemish to send to the opticians. D'Artigues explained to his readers that the English naturally took the lead in making achromatic telescopes for lead crystal had been available in France only for the past twenty-five years, and then only from the largest glass-houses. He went on to explain that the term 'optical flint-glass' should not be applied to any lead crystal, but to that having a density of around 3.3, and the

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[344] A.-G. d'Artigues, *Sur l'art de fabriquer du flint-glass bon pour l'optique*, Paris, (1811). This publication contains a 'Dissertation' (pages 1–6); the text 'Sur l'art de fabriquer du flint-glass bon pour l'optique' (7–55); and a 'Rapport' by Pierre-Simon de Laplace, Louis-Nicolas Vauquelin, Jacques- Alexandre César Charles and Jean-Baptiste Biot, members of the Classe des sciences physiques et mathématiques de l'Institut nationale (56–80).

difficulty arose when making glass of this density. Those who supposed that the denser the glass, the better it would be for optical works were mistaken; such was not the case. When the sand, lead oxide and potash vitrified, the result was often a layered melt, each stratum differing in density, and this could only be overcome by continuing to keep it at a high temperature and by seizing the moment when it was homogenous. The glass was, however, spoilt if fragments of high-lead melt remained at the bottom of the crucible from the previous melt (and Wedgewood's cullet included high-lead glass from lustres); these and numerous suchlike hazards, the result of stray chemical accidents including interaction between the lead oxide and the clay crucible, lay in wait for the would-be optical glass-maker.

D'Artigues had originally fired his furnace with charcoal, keeping the crucibles uncovered, but, running out of locally available firewood, he switched to coal, which was the English practice and necessitated closed crucibles. He decided, however, that open crucibles gave the best results. He discovered that most lead oxide contained a small proportion of copper or iron, which gave the glass a greenish or yellowish tint. The addition of decolourants yielded a glass that lacked clarity, being simply drab in tone. He therefore took care to purify the lead before adding it to the mix. When the glass was ready, the next question was how best to extract the inner parts which alone were optically suitable, for like Wedgwood he found that the upper layer of the melt was a scummy light glass, full of cords, while the bottom layer was too dense and often incompletely mixed. As the mass of glass cooled, it broke into flakes or plates, too small to be of any use. D'Artigues discovered that by allowing the mass to cool very slowly, over a month or more, it broke into plates of a usable size. However, the long cooling period allowed some devitrification, the glass molecules separating into saline glass and lead glass, giving the mass a 'gelatinous' appearance. Undefeated, he then considered another, albeit costly, method of getting the best glass out of the middle of the melt, decanting the glass onto a table, as for mirror plates, and after polishing both sides he might—just might—find some pieces fit for optical working. At the time he lacked the apparatus for this, and resorted to scooping glass from the middle of the melt and flattening it on a metal table. This too was not ideal, for on dipping and retrieving the scoop, some glass from above or beside the desired portion would be taken up. Success came by turning the clock back, technically speaking; taking glass out on the cane, blowing a cylinder, cutting its ends, and flattening it, to level the strata.

The second part of the text details his collaboration with the much-admired optician Robert-Aglaé Cauchoix[345] who had been to Vonêche to assist in the selection of glass plates. Cauchoix had worked astronomical lenses from both small

[345] Article 'Cauchoix' in M. Berthelot (ed.), *La grande encyclopédie*, Paris, (31 vols., 1885–1902), vol. 2, 886.

and large specimens of d'Artigues' glass, and he compared the resulting observations of hard-to-see planetary details with similar glasses from the Dollond workshop—for to French and Italian opticians, Dollond was always taken as the standard. Success was declared. All that was needed was sufficient financial support, combined with a knowledge of chemistry and physics. By taking the upmost care over the preparation and handling, optical-quality flint glass could be made in France to equal that from England. Certainly by the early 1800s telescopes with Cauchoix lenses had made their way into several English observatories.

A Swiss bell-founder, Pierre Louis Guinand, mastered the problem of uneven vitrification. Guinand began by constructing his own spectacle and telescope lenses, then began experimenting with melting his own glass.[346] He equalised the density of the melt by long continued stirring, leaving the whole pot to cool slowly undisturbed. He then broke the pot, obtaining a block from which homogenous fragments could be selected. In 1799 he was able to show Lalande at Paris some flawless discs four to six inches in diameter. Experiments in England were suffocated by the Excise duty, and in France by the lack of demand. Guinand's efforts, and those of his sons, carried this knowledge to Germany. Acclaimed work by the historian Myles Jackson sets out how Guinand collaborated with German craftsman and theoretician Joseph Fraunhofer to produce lenses of remarkable quality that far surpassed British lenses. Jackson's work further details how, in the first half of the nineteenth century, British scientific and state institutions worked together on a series of expensive and disastrous research to reverse engineer Guinand and Fraunhofer's lenses.[347] The production of optical quality glass was an entangled process dependent on numerous factors from individual human skill, through material composition to the way in which these materials were treated. Further these factors were themselves always influenced by concerns of cost patronage and politics. The balance of these considerations in the transmission or appropriation of knowledge of optical glass production continued to preoccupy and frustrate state and private enterprise well into the nineteenth century.

[346] J. F. Chance, *A history of the firm of Chance Brothers. & Co*., London, (1919), 172, n.1.
[347] M. Jackson, *Spectrum of belief: Joseph von Fraunhofer and the craft of precision optics*, Cambridge: MIT Press, (2000).

Chapter Nine
The advancement of skills

Many routes carried lens-working skills to the London workshops over the years. Burning glasses and spectacle lenses were first made in London during the half-century from 1550 to 1600, probably by immigrant craftsmen who had learnt their trade in France and the various adjacent regions. Though there is little conclusive evidence for these activities, the fighting which ranged back and forth as Spain endeavoured to control Flanders and defend it against the Dutch territories may well have encouraged many craftsmen to cross the North Sea to England.[348]

Movement of craftsmen

The arrival of Italian master glass-makers, bringing a knowledge of crystal glass-making as first practiced in the Venetian district of Murano led to advances in British glass-making. The Italian glass-makers were not escaping from persecution. Rather they had been encouraged to emigrate by offer of financial rewards greater than the very real threat of punishment if caught by the Venetian authorities. Over several generations these glass-makers had moved slowly across France and its northern environs, making available a far better quality of glass. They were among the various craftsmen, including miners and metal-workers from central Europe and engravers from Flanders, who were welcomed in England for the new skills they were bringing, skills not available in written form. Often assisted by patronage, they were granted patents and monopolies; in time they acquired denizen rights and in some cases citizenship.

The *cristallo* produced in the Italians' glasshouses was meeting an aristocratic demand for fine domestic glassware, but it was also available for spectacles and mirrors. By the beginning of the seventeenth century the astronomer and mathematician Thomas Harriot discovered, or rather rediscovered, the critical law of refraction (now known as 'Snell's Law'), which was essential for the calculation of sphericity needed for lenses. The 'turnbench' or lathe was already in use for practical and ornamental turning of wood and stone, and could be employed to turn the metal basins on which lenses and spherical mirrors could

[348] The multiplicity of small princedoms, dukedoms, bishoprics and other outposts of major kingdoms changed their borders, grew and faded over the years and have no easy geographical title.

be shaped. Alchemists used such lenses and mirrors to focus the sun's rays and create remarkably high temperatures for their experiments.

Movement of knowledge

The second advance came about in the years immediately after the spy-glass had been invented in about 1608, probably in Middelburg, in the Low Countries. The small spy-glass soon proved its value in military circles. Meanwhile, in England this advance was driven by the enthusiasm of rich patrons— well-educated virtuosi who knew, or believed, that telescopes of astonishing power were being made on the continent, and who wished to possess similar powerful instruments themselves. From their knowledge of mathematics, including the law of refraction, and their reading of current accounts and gossip, backed by correspondence with other virtuosi, they procured *cristallo* glass, guided and instructed the craftsmen, and usually ended up paying exorbitant prices for lenses and telescopes that were items for pleasure rather than practical use. During the late sixteenth and early seventeenth centuries the volume of spectacles imported from France and the Low Countries declined to near zero, presumably indicating the ability of the London craftsmen to supply home demand.

Networks of correspondence developed throughout Europe, along with the physical exchange of samples of glass, lenses, and even a few entire telescopes. Alongside manuscript letters in Latin, French, Italian, Dutch, German and English, printed treatises described methods and machines for grinding lenses. Despite some uncertainty in Jesuit circles as to the truthfulness of images invisible to the naked eye and which could only be seen through telescopes and microscopes, many comprehensive and well-illustrated textbooks were published in the seventeenth century. In elaborate title pages their authors often acknowledged the patronage of the scientifically-minded Habsburg court.[349]

Much effort was wasted on the futile search for non-spherical lenses, which some believed would reduce the troublesome coloured fringes to spherical lenses. Descartes' ideas on this topic were carried further afield by his fame than their accomplishments warranted and others achieved little more. Once the tap of funding dried up, consequent on the development of reflecting telescopes and on various political problems, craftsmen reverted to making the cheaper, smaller and more easily sold lenses for spectacles and microscopes.

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[349] W. B. Ashworth, 'The Habsburg circle', in B. T. Moran (ed.), *Patronage and institutions: Science, technology and medicine at the European court, 1500–1750,* Woodbridge: Boydell, (1991), 137–167, illustrates six 'optical' frontispieces.

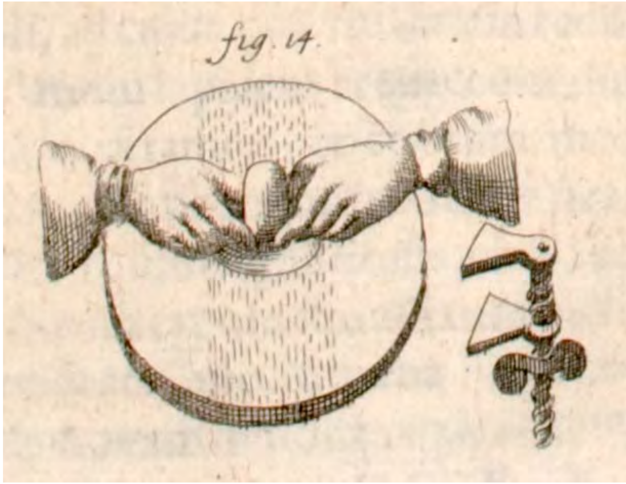

Figure 39: The diagram apparently shows an attempt to manually grind a hyperbolic lens. The lens is ground against a planar surface rather than a typical basin. Further, straight sweeps are employed as opposed to the circular movements that characterised the production of spherical lenses. Johann Zahn, *Oculus artificialis teledioptricus*, Herbipoli: Sumptibus Quirini Heyl, 1685–6, 'Fundamentum III', 'Practico-Mechanicum Fabrica', 34, iconismus V, fig. 14, © Whipple Library, Cambridge, STORE 43:17.

Movement of technology

The third advance came on the back of a more scientific approach to glass-making. With it there came the effort to protect inventions—either by means of patents, or by attempting to restrict the movement of skilled workmen. This craft, which was such a small part of industrial life, was never subjected to the regulations applied to the movements of men engaged in textile or metallurgy manufacture.[350] With the availability of glass of differing refractive indexes, it had been only a matter of time before experimenters in Germany, Sweden and elsewhere challenged Newton's declaration that a colourless image could not be obtained with a refracting telescope. In the 1730s it was discovered that the combination of two lenses of differing shape and refraction—a convex lens of crown glass and a concave lens of dense flint glass—produced an achromatic lens. Doublets of this pattern were produced in London in the 1730s, but in small numbers, until John Dollond patented and publicised this method.

After John Dollond's death his son Peter Dollond, and the few craftsmen whom he licenced, produced considerable numbers of achromatic lenses for which there was now a growing market in Britain and overseas. There was nonetheless a limit to the quantity of 'optically perfect' glass within any pot of glass. Dollond's rate of production and the industry's technical advance was slowed by the increasing imposition of government taxation on glass manufacture. The tax was applied not on the finished products but on all melts, thus making experiments extremely costly. The pottery manufacturer Josiah Wedgewood identified the source of the problem in the stratification caused by incomplete mixing in the crucible. However, inhibited by the sanctions of the Excise, Wedgewood did not publicise his findings. The history of early modern optical

[350] See for example, J. R. Harris, *Industrial espionage and technology transfer: Britain and France in the eighteenth century*, Aldershot: Ashgate, (1998).

glass is a melting point of human skill and movement with cost, materials, patronage, and politics. The balance of these considerations in the transmission of knowledge continued to preoccupy and frustrate state and private enterprise well into the nineteenth century.

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