Practical Optics and Polemical Purposes in Seventeenth-Century England

James Everest

UCL

I, James Everest, confirm that the work presented in this thesis is my own. Where information has been derived from other sources, I confirm that this has been indicated in the thesis.

In memoriam Lisa Jardine

Contents

Abstract

What follows is a study of the prevalence and value of practical work in seventeenth-century English optics. I argue, firstly, that practical work – involving instruments and experiments – was a major aspect of the discipline at this time and, secondly, that a major purpose of this work was what I call 'polemical' in character. The first claim is directed at histories of seventeenth-century optics, which have tended to focus on the development of theories about light and vision, at the expense of the practical work that was such a prominent feature of the field. The second claim is directed at works on the 'rhetoric of science', which have tended to focus on a scientist's deployment of various means, such as practical work, in a bid to persuade an audience that he or she is right about an aspect of the natural world, whereas my take on seventeenth-century natural philosophy is that practical work could serve another important function: it could act to persuade an audience that the ideas of a rival were wrong.

The four chapters take the form of case-studies, examining in detail the practical work of Francis Bacon, Thomas Hobbes, Robert Hooke and Isaac Newton, each man the leading English optical philosopher of his generation. Each chapter supports the first claim of the thesis, by emphasising its subject's practical work in optics; each supports the second, by highlighting the polemical purposes to which that practical work was turned. In addition, each chapter identifies the audiences before whom practical work was deployed, with the result that the four chapters can be read as a narrative, one that charts the expanding audiences for practical work in the seventeenth century. A prominent take on the increasingly public character of natural philosophy in this period stresses the quest for assent and the desire to manage dissent. The story told here, by contrast, emphasises the ongoing presence of a disorderly spirit of dispute.

Acknowledgements

My thanks are due, firstly, to my supervisors, Lisa Jardine and Angus Gowland. I began the thesis at Queen Mary, University of London, and ended it at UCL, and have benefited from the intellectual atmosphere at both institutions. Meanwhile, staff at the Royal Society library provided a hospitable working environment for much of the research. Parts of what follows were read in draft form by Felicity Henderson, James Lancaster, Noah Moxham, Richard Serjeantson, Erin Webster and Clare Whitehead; I am grateful for their advice and encouragement. Waseem Yaqoob and Susan Everest went through the whole thing and provided valuable suggestions. Final and special thanks belong with my family: it is no hyperbole to say that without them the thesis would not have been completed.

Notes on Dates

In seventeenth-century England, the new year officially began on 25 March, so anything dated, for example, ‘2 January 1663’ belongs to what we would call 1664. In addition, the calendar was 10 days behind the one used today, so ‘2 January’ in fact corresponds to what we would think of as 12 January. In what follows, I have silently updated the year where appropriate, but have maintained the original date of the month. Items that crossed national borders, such as letters, pose a particular problem, as Catholic Europe had already adopted the calendar that is now employed worldwide. I have followed the contemporary practice of providing both old- and new-style dating, e.g. ‘2/12 January’.

Notes on Transcriptions

When quoting from manuscript sources, I have preserved as many features of early modern scribal activity as possible, including contractions, superscript and ligatures. For the sake of clarity, however, I have dropped words or passages that are struck through in the original (except where they prove revelatory); similarly, I have not identified text that is a marginal or intralinear insertion as such. In both cases, my intervention is mentioned in the notes.

Introduction

1. Practical Optics

In 1772, the dissenting clergyman and practising natural philosopher Joseph Priestley published a book on optics, *The History and Present State of Discoveries Relating to Vision, Light, and Colours*, a sequel to the hugely successful *History and Present State of Electricity*, his first foray into the field now thought of as the 'history of science'. In the opening lines of the earlier work, he outlines his intentions: "I flatter myself that I shall give pleasure [...] and I hope the work will be of some advantage to the science [of electricity] itself"[1]. What kind of pleasure does he have in mind? It is, he claims, not unlike "that of the sublime [...] For an object in which we see a perpetual progress and improvement is, as it were, continually rising in its magnitude; and moreover, when we see an actual increase, in a long period of time past, we cannot help forming an idea of an unlimited increase in futurity; which is a prospect really boundless, and sublime"[2]. What kind of advantage, meanwhile, does he think will accrue from such a sublime prospect? "Great conquerors", he writes, "have been both animated and also, in a great measure, formed by reading the exploits of former conquerors. Why may not the same effect be expected from the history of philosophy to philosophers?"[3] When it comes to the history of natural philosophy, he concludes, "an intimate knowledge of what has been done before us cannot but greatly facilitate our future progress, if it be not absolutely necessary to it"[4].

[1] Priestley, *History of Electricity*, i.
[2] *Ibid.*, ii.
[3] *Ibid.*, v.
[4] *Ibid.*, vi.

Priestley is, of course, conscious that a history of all the various branches of natural philosophy would be an immense project, "perhaps more than any one man ought to undertake". Here, accordingly, he limits himself to "that branch which has been my own favourite amusement", the study of electricity, with the hope that his book will encourage "other persons to do the like for theirs"[5]. His choice of subject-matter is, however, unquestionably exciting: "Few branches of Natural Philosophy [...] can boast such a number of discoveries, disposed in so fine a series, all comprised in so short a space of time, and all so recent, the principal actors in the scene still living"[6].

The literate public seems to have agreed: the book was a commercial and critical triumph. Five years later, Priestley was back with his sequel, *The History and Present State of Discoveries Relating to Vision, Light, and Colours*. As we have seen, he had previously considered the study of all the branches of natural philosophy to be beyond the scope of any one man's labour, but success in his first venture seems to have prompted a change of heart: "like the fox with respect to the lion, a nearer view has familiarized it to me, and I now look upon it not only without dread, but with a great deal of pleasure; considering it not only as a very practicable *business*, but even as an agreeable *amusement*"[7]. The new book is devoted to optics, a field of activity that, Priestley suggests, offers "a number of the finest gradations in the discoveries of different persons, a view of the greatest and happiest exertions of human genius, and the labours of those who are the most celebrated for their philosophical pursuits"[8]. Unfortunately, his readers were less enthused a second time around: although

[5] *Ibid*., vii.
[6] *Ibid*., viii (mispaginated vii).
[7] Priestley, *History of Light, Vision and Colours*, iii.
[8] *Ibid*., x.

favourably reviewed, the work was a commercial flop and his project for histories of the remaining branches of natural philosophy died with it[9].

A disaster for Priestley, *The History and Present State of Discoveries Relating to Vision, Light, and Colours* is a valuable source for historians seeking an insight into the priorities of early modern natural philosophers undertaking work in optics[10]. Perhaps as a consequence of Priestley's conception of history as an aid to future progress, the book is overwhelmingly concerned with the recent past. It is divided into six 'periods': the first a brief account of developments up to 'the revival of letters in Europe'; the second a description of work dating to the sixteenth and early seventeenth centuries; the third a survey of the discoveries of René Descartes and his contemporaries; the fourth an overview of later seventeenth-century activity; the fifth a study of the work of Isaac Newton; and the sixth an account of developments since. He concludes by sketching some directions that future research could take.

The obvious (because most recent) point of comparison is A. Mark Smith's *From Sight to Light*, a history of optics from antiquity to the seventeenth century, published in 2014. Unlike Priestley, Smith devotes equal weight to each of the periods in his narrative, constructing a tale that moves from Greek and Roman science, to developments in the Arabic world, to the medieval Latin West and the Renaissance. Like Priestley, however, Smith writes with one eye turned to the present, not with the goal of furthering the progress of optics, but with that of explaining the modern manifestation of the discipline. In the opening lines of his preface, he observes: "The

---

[9] Priestley's project for a complete history of natural philosophy is outlined in Schofield, *The Enlightenment of Joseph Priestley*, 138-52 and 240-9.
[10] Geoffrey Cantor makes a similar use of Priestley's book in his study of eighteenth-century optics; see *Optics after Newton*, 8-9.

merest glance at any modern optics textbook leaves no doubt that, as currently understood, the science of optics is about light". "But", he continues, "this understanding of optics and its appropriate purview is relatively new. For the vast majority of its history, the science of optics was aimed primarily at explaining not light and its physical manifestations, but sight in all its aspects"[11]. He locates the shift in focus in the seventeenth century and attributes it to the publication in 1604 of Johannes Kepler's theory of retinal imaging, dubbing it, as a result, the 'Keplerian turn'. This shift – from sight to light – provides the title for his book; his subtitle glosses it as 'the passage from ancient to modern optics'.

Looking to the past for an explanation of the modern manifestation of a discipline can, of course, be a risky thing to do: all too easily, historical change can start to seem predetermined and a historical actor's experience of their work can be lost, together with their capacity to surprise and challenge us. Smith is clearly aware of the risks and looks to obviate them, by consistently placing the intellectual activity that he describes in the context of a contemporary 'marketplace of ideas'. In his introduction, he aligns his approach with the current historiographical emphasis on what is known as the 'social construction' of scientific knowledge and discusses it with reference to what could otherwise look like his unduly 'Western' perspective, for example in his decision to focus on the seventeenth-century Dutch astronomer Willebrord Snel's discovery of the sine law of refraction, rather than on that of the tenth-century Arabic mathematician Ibn Sahl. "Whereas", he writes, "there appear to have been no buyers in Ibn Sahl's marketplace, there was a brisk trade in Snel's. It was therefore in the 'West', not the

[11] Smith, *From Sight to Light*, ix.

'East', that the sine law became historically significant and meaningful as it was there that it became communal and fruitful"[12].

The History and Present State of Discoveries Relating to Vision, Light, and Colours provides some evidence in support of A. Mark Smith's narrative. Although the title seems to place Priestley's book in a transitional moment, in which the focus of optics was shifting from sight to light, the work as a whole supports Smith's contention that this change properly belongs to the seventeenth century: much of Priestley's history is, in fact, concerned with discoveries relating to the nature and behaviour of light.

There are, however, some intriguing points of divergence. Priestley's second period, which takes his story from 'the revival of letters in Europe' to the early seventeenth century, is comprised of five sections, with the first bearing the title: "Discoveries in opticks independent of telescopes and microscopes, and before those of Kepler"[13]. Like Smith, Priestly here seems to think of Kepler as a significant figure, postponing the discussion of his work. He also, however, seems to attach some importance to the invention of the telescope and microscope. When Kepler re-appears, it is in a section on "Miscellaneous discoveries of *Kepler* and his Cotemporaries", phrasing that does not suggest the central position that the theory of retinal imaging occupies in Smith's book[14]. When telescopes and microscopes re-appear, by contrast, it is in a section devoted exclusively to their invention and 'first improvements', a decision that suggests that, for Priestley, they are the more important feature of the period[15].

---

[12] *Ibid*., 9. He aligns his approach with those pursued in Shapin, *A Social History of Truth*, and Shapin and Schaffer, *Leviathan and the Air-Pump*.
[13] Priestley, *History of Light, Vision and Colours*, 29.
[14] *Ibid*., 82.
[15] *Ibid*., 55.

Smith, it is true, includes a section on the invention and development of telescopes and microscopes in his chapter on the optical work of the seventeenth century, but he clearly considers these devices to be less significant than the 'Keplerian turn' that is outlined in the preceding chapter[16]. Indeed, the hierarchy is clear from the title of the later chapter: 'The Seventeenth-Century Response'. By contrast, Joseph Priestley begins his section on telescopes and microscopes: "It was in this period of my history that mankind began to derive an advantage from the science of opticks"[17]. His verdict reminds us of the hope, expressed in the opening to *The History and Present State of Electricity*, that the work will be a subject of both pleasure and advantage. In fact, Priestley also lays stress on the pleasure that is to be gained from the use of telescopes and microscopes; "By means of these instruments", he writes, "the bounds of human knowledge have been amazingly extended, and by the same helps new and exhaustless sources of information and pleasure are continually opening to us; so that a person who is possessed of these instruments, and who has a taste which every man ought to be ashamed to be destitute of, can never want subjects of the most rational entertainment"[18].

Priestley's emphasis on the "rational entertainment" afforded by telescopes and microscopes echoes some of the accounts provided by their earliest users. In the opening pages of the *Sidereus nuncius* of 1610, for example, Galileo Galilei writes that "to look at the body of the Moon, which is removed from us by almost sixty terrestrial diameters, and to see it as if it were only two diameters away" is "a most beautiful and

[16] Smith, *From Sight to Light*, 381-91.
[17] Priestley, *History of Light, Vision and Colours*, 55.
[18] *Ibid*., 55-6.

a very pleasing sight”[19]. Similarly, “to be able to point out the nature of those stars that all astronomers have hitherto called nebulous, and to show that it is very different from what was believed until now” is “a fine and pleasant thing”[20]. In the *Novum organum* of 1620, Francis Bacon describes the “remarkable enterprise” that led to these telescopic observations and the “astonishment” with which, by means of a similar instrument, one can discern “the exact shapes and lineaments in a flea, fly or worm”[21]. Forty-five years later, Robert Hooke included in *Micrographia*, his celebrated compendium of microscopic engravings, a famous image of a flea (figure 1) and rhapsodised in his introduction: “By the means of *Telescopes*, there is nothing *so far distant* but may be represented to our view; and by the help of *Microscopes*, there is nothing so *small*, as to escape our enquiry”. He continues:

> By this means the Heavens are open’d, and a vast number of new Stars, and new Motions, and new Productions appear in them, to which all the antient Astronomers were utterly Strangers. By this the Earth it self, which lyes so neer us, under our feet, shews quite a new thing to us, and in every *little particle* of its matter, we now behold almost as great a variety of Creatures, as we were able before to reckon up in the whole *Universe* it self[22]

[19] *Pulcherrimum, atque visu iocundissimum est, Lunare corpus per sex denas ferè terrestres diametros à nobis remotum, tam ex propinquo intueri, ac si per duas tantum easdem dimensiones distaret*, Galilei, *Sidereus nuncius*, B1^{r-v}, translated in *Galileo’s Sidereus Nuncius*, 55.

[20] *insuperquè substantiam Stellarum, quas Nebulosas hucvsquè Astronomorum quilibet appellauit digito demonstrare, longèque aliam esse quam creditum hactenus est, iocundum erit, atque perpulcrum*, Galilei, *Sidereus nuncius*, B1^{v}, translated in *Galileo’s Sidereus Nuncius*, 56. William Shea translates the phrase “digito demonstrare” as “to point out, as with one’s finger”.

[21] He describes Galileo’s work as “*memorabili conatu*” and writes: “*in Pulice, Muscâ, Vermiculis, accurata corporis figura & lineamenta* […] *non sine admiratione cernuntur*”, *Novum organum*, 342-4, translated on 343. Graham Rees highlights Bacon’s evident familiarity with telescopes and microscopes in his introduction to *The Oxford Francis Bacon 11*, xl.

[22] Hooke, *Micrographia*, a2^{v}.

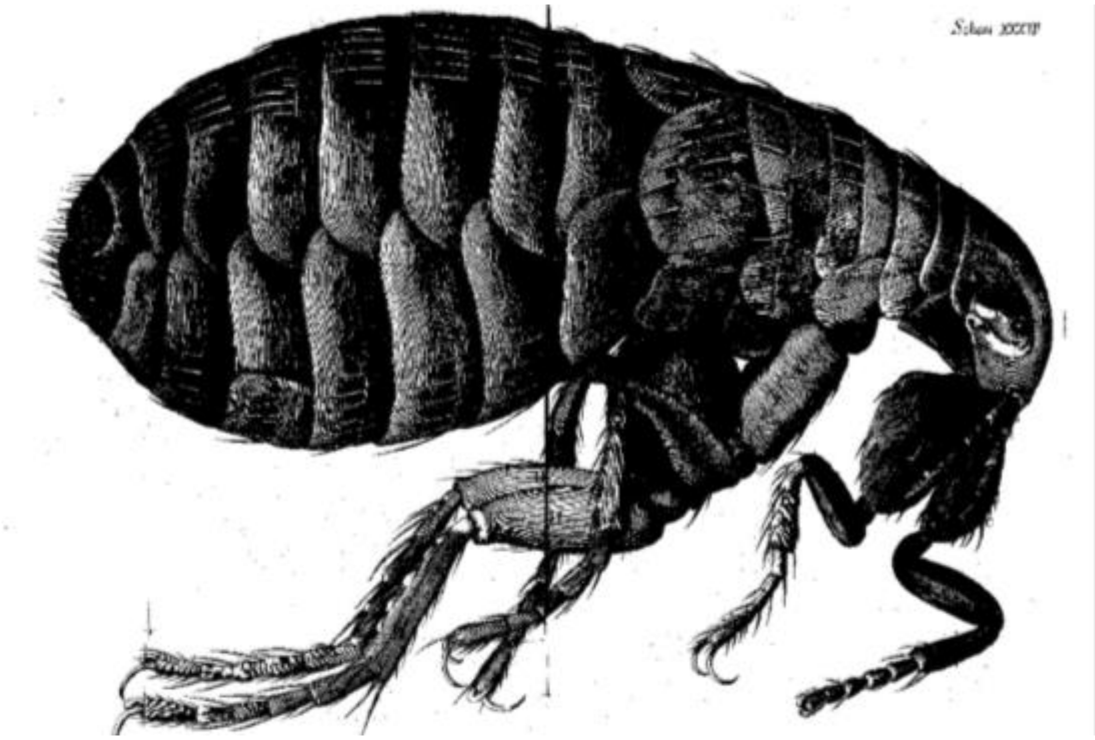


Fig. 1 Robert Hooke, *Micrographia*, figure 34, inserted between Ff1^{v} and Ff2^{r}.

On the whole, academic studies of seventeenth-century telescopy and microscopy have not been as effusive as they could about the pleasurable sense of wonder that was engendered by these new devices, although Marian Fournier's work on the microscope contains some evocative passages: "The breathtaking complexity and variety of organic nature", she writes, for example, "formed a welcome subject for the studies of the average amateur of science, proving to his admiring eyes beyond question the omnipotence of God"[23]. If anything, she understates the case: it seems clear that the

[23] Fournier, *The Fabric of Life*, 5. Albert van Helden's 'The Invention of the Telescope' remains a valuable account of the rise of telescopy, but see also the essays collected in *The Origins of the Telescope*, edited by van Helden, Sven Dupré, Rob van Gent and Huib Zuidervaart, as well as Reeves, *Galileo's Glassworks*, and Willach, *The Long Route*. For microscopy, see also Ruestow, *The Microscope in the Dutch Republic*, and Wilson, *The Invisible World*. The two volumes of Philippe

philosophers who peered through these murky, often malfunctioning tubes were utterly captivated by what they saw. In fact, as Stuart Clark observes in his discussion of vision in early modern intellectual culture, the extraordinary character of the spectacles made newly possible in these years was so remarkable that, for some contemporaries, these instruments presented a powerful challenge to the security of what they saw, or thought they saw, on an everyday basis[24].

The other obvious point of divergence between A. Mark Smith and Joseph Priestley's histories of optics arises from the former's discussion of the conceptual and cultural contexts in which we should view the 'Keplerian turn'. He describes the rise of atomism and the importance of mathematics, before turning to the twin currents of scepticism and empiricism: "perhaps somewhat paradoxically", he writes, "a host of seventeenth-century scientific thinkers embraced empiricism warmly and, with it, the 'Experimental Philosophy' godfathered by Francis Bacon and avidly promoted by Robert Boyle"[25]. This is the only use of the phrase 'experimental philosophy' in the book, a *hapax legomenon* that contrasts strikingly with Joseph Priestley's liberal use of the term as a description of the subject-matter for his expansive historical project. At no point does Priestley seek to clarify or justify his use of the phrase, an omission that suggests that, for him, it needs no explanation: for Priestley, a branch of natural philosophy, such as optics, simply is a branch of experimental philosophy.

Hamou's *La Mutation du visible* cover both. For the power of wonder in this period, see Campbell, *Wonder and Science*, Daston and Park, *Wonders and the Order of Nature*, and the essays published in Deckard and Losonczi, eds., *Philosophy Begins in Wonder*.

[24] Clark, *Vanities of the Eye*, 102 and 350-1. He makes the point with reference to the works of Athanasius Kircher and Joseph Glanvill.

[25] Smith, *From Sight to Light*, 379.

The importance of the term 'experimental philosophy' in the seventeenth century has been emphasised in a recent essay by Peter Anstey[26]. More broadly, the rise of experimental science and its relationship with physics and mathematics are the province of Peter Dear's *Discipline and Experience*, published in 1995. Experiments are, of course, a fundamental feature of modern science and explaining how they assumed such a prominent position is a large and important task. Just as an attempt to explain the modern manifestation of a scientific discipline can be a risky business, however, so can an attempt to explain a fundamental feature of modern scientific practice. Like A. Mark Smith, Peter Dear seems aware of the risks: in his introduction he stresses his focus on the contemporary 'discourse' surrounding experimental activity, a term that he uses in a broad, Foucauldian sense. He describes his work as the examination of "commonalities of linguistic philosophical practice", looking at "how people [...] talked about how to make natural knowledge or justified their philosophical work", with his aim the "recreation" of a "philosophical culture"[27].

Optics certainly has a prominent place in the culture that Peter Dear recreates. In fact, he concludes his final chapter with a discussion of what is surely one of the most famous accounts of seventeenth-century experimentation: Isaac Newton's letter, sent to the Royal Society in February 1672, in which he describes the work with prisms that led him to his theory of the heterogeneous nature of light (the idea that so-called 'white' light consists of a series of colours that refract at different angles)[28]. Dear compares the style in which the letter is written with that deployed in Newton's previous lectures on

---

[26] Anstey, 'Experimental versus Speculative Natural Philosophy'.
[27] Dear, *Discipline and Experience*, 4-5.
[28] Letter 40, in Turnbull, Scott, Hall and Tilling, eds., *The Correspondence of Isaac Newton*, vol. 1, 92-107. The letter was subsequently published in the Society's journal, the *Philosophical Transactions*. For a recent commentary, published to celebrate the 350th anniversary of the journal, see Fara, 'Newton Shows the Light'.

the subject, which, he writes, "adhered closely to the usual form for geometrical optics. The texts proceed discursively from point to point, but Newton nonetheless presents formal demonstrations of his 'propositions' as he goes along"[29]. The letter, by contrast, adopts a "determinedly anecdotal, event-focussed style", which "restructures the material of the lectures into a story of the discovery of universal properties of light"[30]. This restructuring process, meanwhile, is clearly related to Newton's target audience: he presents his approach "as if it simply conformed to the logic of the Royal Society's experimental philosophy"[31].

Newton's experiments with prisms appear, somewhat briefly, in A. Mark Smith's history of optics, towards the end of a section on colour that is part of his chapter on the seventeenth-century 'response' to Kepler's theory of retinal imaging[32]. In Joseph Priestley's study, by contrast, Newton is a monumental figure, his work in the field the subject of an entire period, the first section of which is devoted exclusively to the theory of the heterogeneity of light. In his introduction to this part of the book, Priestley writes: "Of all the discoveries that have been made concerning the nature of light and colours, there are none that make anything so great a figure as those of Sir Isaac Newton"[33]. He continues with a survey of previous theories about colour, before concluding: "After these random conjectures, unsupported by a shadow of evidence, or so much as an attempt at experimental proof, with what satisfaction is it, that we, at length, come to the discovery of a theory of light and colours, striking and beautiful in itself, drawn from the clearest and most decisive experiments"[34].

---

[29] Dear, *Discipline and Experience*, 232.
[30] *Ibid*., 234.
[31] *Ibid*., 235.
[32] Smith, *From Sight to Light*, 405-7.
[33] Priestley, *History of Light, Vision and Colours*, 238.
[34] *Ibid*., 241.

From the perspective of the modern manifestation of the discipline, then, the most important feature of seventeenth-century optics is the shift from sight to light that A. Mark Smith attributes to the publication of Johannes Kepler's theory of retinal imaging in 1604. From the perspective of a historian writing in the following century, on the other hand, two aspects of the period appear more significant: the invention of telescopes and microscopes and the development of an experimental philosophy.

It seems to make sense to consider these two things – optical instruments and optical experiments – in conjunction (and not simply because of the tendency for everyday objects to turn into 'scientific instruments' once they have been deployed in an experimental context[35]). Both testify to a fundamental truth about the nature of early modern natural philosophy: its practical character. For a hypothetical adherent of the Aristotelianism that had previously dominated the field, the idea that a branch of science could involve 'practical knowledge' presents something of a problem, the two parts of the phrase corresponding to dramatically different intellectual virtues, *technê* and *epistêmê*[36]. I refer to a 'hypothetical' Aristotelian as it is worth asking whether anybody (even Aristotle) ever thought of the distinction in quite the stark terms that are employed in Book VI of the *Nicomachean Ethics*[37]. Nevertheless, it clearly went through a time of particular muddiness in the early modern period, especially in the seventeenth century, with Francis Bacon the most famous and most influential advocate of what he termed *scientia operativa*[38].

[35] Simon Schaffer tracks the contested status of Newton's prisms in 'Glass Works'. For a classic study of the place of an instrument in seventeenth-century experimental practice, see Shapin and Schaffer, *Leviathan and the Air-Pump*.
[36] Aristotle, *Nicomachean Ethics*, 1139. He introduces a third term, *phronêsis*, which corresponds to something like 'practical knowledge', but he uses it to refer to ethics.
[37] For a discussion of Aristotle's more nuanced use of the terms elsewhere in his work, see Parry, '*Episteme* and *Techne*'.
[38] See Klein, 'Francis Bacon's *Scientia Operativa*', and Weeks, 'The Role of Mechanics in Francis Bacon's Great Instauration'.

In the introduction to *From Sight to Light*, Smith describes his book as a "revamping" of David Lindberg's classic study, *Theories of Vision from al-Kindi to Kepler*[39]. More generally speaking, it could be viewed as the heir to a broad tendency in the history of optics to favour theory over practice, to emphasise ideas about the nature and behaviour of light and vision – ideas expressed, for the most part, in mathematical forms – at the expense of a focus on the use of instruments and experiments. In the preface to *A History of Optics from Greek Antiquity to the Nineteenth Century*, for example, Olivier Darrigol describes one of the steps, like the use of modern mathematical notation, that he has taken simply for the purposes of economy: "I give details of optical experiments", he writes, "only when they matter to the conceptual developments"[40]. When it comes to prominent surveys of seventeenth-century work in the field, Alan Shapiro's 'Kinematic Optics' is a study of the 'wave' theory of light articulated by Thomas Hobbes, Robert Hooke and Christiaan Huygens[41]. Meanwhile, the title of A.I. Sabra's *Theories of Light from Descartes to Newton*, like that of David Lindberg's book, betrays its author's sense of priorities[42].

And yet, there is clearly a practical spirit active in the intellectual endeavours of the age. The starting-point for this study is what I consider the more than coincidental relationship between the contemporary emphasis on the use and understanding of instruments – a field of activity known as 'mechanics'[43] – and the ascendancy of an experimental philosophy. The investigation of nature in this period was dominated by

---

[39] Smith, *From Sight to Light*, 4.
[40] Darrigol, *A History of Optics*, vi.
[41] Shapiro, 'Kinematic Optics'.
[42] Sabra, *Theories of Light from Descartes to Newton*.
[43] See Bennett, 'The Mechanics' Philosophy and the Mechanical Philosophy' and 'Early Modern Mathematical Instruments', Daumas, *Scientific Instruments of the Seventeenth and Eighteenth Centuries*, Rossi, *Philosophy, Technology and the Arts*, Smith, *The Body of the Artisan*, van Helden, 'The Birth of the Modern Scientific Instrument', and the articles collected in Lefèvre, ed., *Picturing Machines*.

practical philosophers, men and women who made great leaps forward in the human understanding of the world by means of their ability to handle instruments and carry out experiments. It certainly seems worth examining the use of both optical instruments and optical experiments under the banner of 'practical optics'.

2. Polemical Purposes

The first goal of this thesis is to highlight the importance of practical work in seventeenth-century optics. Like Peter Dear, however, my aim is also to recreate the philosophical culture in which that work occurred. Like him, my subject is "how people talked about what they did", with the idea that "what they did can only be characterised and understood by their forms of speech about it"[44]. Each chapter involves a consideration of who the intended audience for pieces of scientific activity may have been and how that audience may have shaped the ways in which it was conducted and presented. In particular, my intention is to emphasise the extent to which this culture was what I call 'polemical' in character[45]. In a scholarly environment that is comfortable with the idea that scientific knowledge is socially constructed, it seems uncontroversial to suggest that seventeenth-century philosophers may have deployed instruments and experiments as part of a bid to convince an audience that they were correct in their claims about an aspect of the natural world. The point that I want to press is that practical work was also valuable for its capacity to convince an audience that another philosopher was wrong.

[44] Dear, *Discipline and Experience*, 5.
[45] I use the word in the primary sense recorded in the *Oxford English Dictionary*: "Of the nature of, exhibiting, given to, or relating to dispute or controversy; contentious, disputatious, combative".

This idea is likely to surprise few historians of early modern intellectual culture. In fact, my approach could be viewed as the wholesale adoption of Quentin Skinner's focus on the combative rhetorical context surrounding the deployment of concepts, if we extend the term 'concept' such that it applies not simply to moral or political ideas, but also to notions about the workings of the natural world. In the conclusion to a volume of essays dedicated to his conception of historiographical method, Skinner suggests that one way of expressing the principle that underlies his work would be "to say that I wanted to treat the understanding of concepts as always, in part, a matter of understanding what can be done with them in argument". He continues, by identifying an assumption that he shares with another great historian of concepts, Reinhart Koselleck: "we need to treat our normative concepts less as statements about the world than as tools and weapons of debate". He concludes: "Both of us have perhaps been influenced by Foucault's Nietzschean contention that 'the history which bears and determines us has the form of a war'"[46].

The idea is also likely to surprise few historians of science, who are well aware of the various spats that punctuated work in seventeenth-century natural philosophy, with the conflict between Isaac Newton and Robert Hooke following the former's letter to the Royal Society on the heterogeneous nature of light perhaps the most famous[47]. Since the 1980s, moreover, historians of science have been devoting considerable attention to what has become known as the 'rhetoric of science'. In the introduction to a landmark collection of essays, published in 1991, Peter Dear describes an "increasing sensitivity to the lesson, developed in other disciplines, that language is not simply a transparent

[46] Skinner, 'Retrospect: Studying Rhetoric and Conceptual Change', 177. The reference is to *Power / Knowledge,* 114.
[47] I discuss aspects of this conflict in chapters three and four.

medium of communication, but a shaper (perhaps a realiser) of thought and an embodiment of social relations"[48]. In a contribution to the recent multi-volume *Cambridge History of Science*, Richard Serjeantson highlights the importance that notions of 'proof' and 'persuasion' have for historians of an age that saw both "more self-conscious theoretical reflection on how to discover and confirm the truths of nature than any period before or since" and "a huge range of practical strategies by which investigators of the natural world set about demonstrating their findings and convincing their audiences of their claims"[49].

There are, of course, a couple of epistemological issues underlying Serjeantson's discussion. The first concerns the difference between the 'discovery' and the 'confirmation' of the truths of nature, a distinction that philosophers of science traditionally refer to as the 'context of discovery' and the 'context of justification'[50]. The second involves the difference between the idea that an investigator 'demonstrates' their findings and the idea that he or she 'convinces' an audience. Some rhetoricians of science have sought to collapse both distinctions. In the opening pages of his high-profile *The Rhetoric of Science*, for example, Alan Gross pithily defines "the creation of knowledge" as "a task beginning with self-persuasion and ending with the persuasion of others"[51]. A little later, he declares his conviction that the practice of science is rhetorical, "without remainder"[52], a phrase that has set a fair few teeth on edge[53]. For a historian, the wisest course seems to be to steer clear of epistemological judgements.

[48] Dear, 'Introduction', in *The Literary Structure of Scientific Argument*, 4-5.
[49] Serjeantson, 'Proof and Persuasion', 132.
[50] For an overview of the distinction, see Schickore, 'Scientific Discovery'.
[51] Gross, *The Rhetoric of Science*, 3.
[52] *Ibid.*, 33.
[53] The most prominent example is Gaonkar, 'The Idea of Rhetoric in the Rhetoric of Science'. For a recent overview of Gross's work, see Harris, 'Alan Gross and the Rhetoric of Science'.

Seventeenth-century philosophers were clearly persuaded by the information that they gained from instruments and experiments and they clearly used this information in ways that served to persuade an audience of their claims. What the nature of that persuasion is – whether or not it is rhetorical without remainder – is not a question that I feel qualified to pursue.

The emphasis placed by rhetoricians of science on the extent to which scientific activity consists of persuading an audience invites the question: what exactly is the scientist – or, in my case, the early modern natural philosopher – trying to persuade their audience of? The obvious answer, implicit in all the studies of scientific rhetoric referenced above, is: that he or she is correct in their assertions about an aspect of the natural world. This response entails a vision of the intellectual community, one in which individual members deploy various strategies – including, in this case, the use of information derived from instruments and experiments – to further the social construction of knowledge, by convincing an audience of the veracity of their claims. The picture that emerges is of a raucous, competitive world, one in which individuals strive for the attention and approval of their peers. It is, in short, a picture not unlike that conjured by A. Mark Smith's invocation of a 'marketplace of ideas'.

There is, however, another answer to the question: as the editors of a 1991 volume of essays, *Persuading Science*, observe in their preface, persuasion can involve both "the presentation of arguments to an audience" and "the refutation of opponents", a twofold description that, to my mind, successfully captures the character of seventeenth-century natural philosophy[54]. In what follows, I will be pursuing the second half of the equation,

[54] Pera and Shea, 'Preface', in *Persuading Science*, ix.

emphasising the polemical dimension to practical work in optics, by stressing the capacity of such work to convince an audience not so much that the philosopher deploying it is right, but that another philosopher is wrong. In the vision of the intellectual community that comes with this approach, it is not only a raucous and competitive place, but also a confrontational one, less A. Mark Smith's marketplace of ideas and more Quentin Skinner's battleground. The difference is perhaps principally one of metaphor, but, as a number of rhetoricians of science have emphasised, a choice of metaphor can sometimes prove significant[55].

3. Seventeenth-Century England

The location of this battleground is seventeenth-century England, a geographical focus that I do not intend as a suggestion that the currents I describe were not present in continental Europe and beyond: rather, my goal in limiting the subject in this way is to allow sustained attention to the ways in which transnational trends played out across the century within a particular country. My close focus also acts as a counterbalance to the tendency in some histories of optics to take a continental perspective, only dropping into England at the formation of the Royal Society in 1660[56]. There may, indeed, be an even more resolutely English story to be told than the one that I have laid out here, one that would build on the place of mechanics in sixteenth-century English culture and on the thriving artisanal world described in Deborah Harkness's *The Jewel House*[57]. I have not gone particularly far down this road, as the attention that I have brought to bear on

[55] Jeanne Fahnestock devotes a section of the opening chapter of *Rhetorical Figures in Science* to 'The Dominance of Metaphor', 4-6, a phrase she uses to refer to the dominance of the attention paid to metaphor within work on the rhetoric of science, at the expense of other rhetorical figures.
[56] To be fair, this tendency is most evident in works seeking to reach a broad audience: see, for example, Ronchi, *The Nature of Light*, and Park, *The Fire Within the Eye*.
[57] For the place of mechanics in sixteenth-century English culture, see Ash, *Power, Knowledge and Expertise in Elizabethan England*, and Wolfe, *Humanism, Machinery and Renaissance Literature*.

optical work dating from the first half of the seventeenth century has, in fact, served to emphasise the extent to which it should be read within a European context. Nevertheless, I hope that one outcome of the thesis is to emphasise the existence of local antecedents to the activity conducted by the early members of the Royal Society.

In pursuing the English tradition of practical optics, I have adopted a case-study approach, examining in some depth the work of four key figures: Francis Bacon, Thomas Hobbes, Robert Hooke and Isaac Newton. The presence of Hobbes, Hooke and Newton will be obvious enough to most readers – all three feature prominently in studies of seventeenth-century optics[58] – but the selection of Francis Bacon perhaps deserves a brief word of explanation, not only as he is not necessarily an obvious candidate for inclusion, but also because there is an obvious alternative in the person of Thomas Harriot. The former's role as a standard-bearer for practical science is firmly established, but the idea that he deserves a place in a history of optics is likely to be greeted with some raised eyebrows. By contrast, it is generally well-known that the latter arrived at the sine law of refraction before Willebrord Snel and trained a telescope on the surface of the Moon before Galileo[59].

Compared with such accomplishments, Bacon's activity in the field will no doubt appear paltry. And yet, by another criterion he is the more significant figure. Almost all

[58] A.I. Sabra, for example, devotes sections of *Theories of Light* to Hooke, 187-95, and to Newton, 231-50. Alan Shapiro dedicates sections of 'Kinematic Optics' to Hobbes, 143-72, and to Hooke, 188-207. Hobbes and Hooke appear in a section of Olivier Darrigol's chapter on seventeenth-century optics in his *A History of Optics*, 49-59, and he devotes a chapter to Newton, 78-108. References to Hooke and Newton appear in A. Mark Smith's chapter on 'The Seventeenth-Century Response' in *From Sight to Light*, at 386-7, 390, 397, 403-9 and 415.

[59] For an overview of Harriot's discovery of the law of refraction, see Goulding, 'Thomas Harriot's Optics', 143-50. Credit for identifying his discovery is due to John W. Shirley and J.A. Lohne; see 148-50. For his selenography, see Alexander, 'Lunar Maps and Coastal Outlines', and Pumfrey, 'Harriot's Maps of the Moon'.

of Harriot's accounts of his intellectual achievements remained unpublished in the decades following his death in 1621[60], with the result that his impact amounted to what the historian of mathematics Rosalind Tanner has called "a legacy of hearsay"[61]. Bacon's work on light, on the other hand, was widely available, to some extent in the *Novum organum*, but more obviously in the *De augmentis scientiarum* of 1623 and, in a more developed form, in the *Topica inquisitionis de luce et lumine*, which appeared as part of a posthumous collection of small works, the *Opuscula varia posthuma*, in 1658[62]. I have already hinted that a reference in the *Novum organum* to the astonishing appearance of a flea when viewed through a microscope may have been a factor in Hooke's inclusion of a drawing of the animal in his *Micrographia*. An experiment proposed by Bacon in the same work – to focus the light of the Moon with a burning glass – was carried out by Robert Boyle, with the results published in his book on the nature of cold of 1664[63]. Meanwhile, the emphasis throughout Bacon's work on glow-worms and rotten fish and wood as examples of things that emit light but not heat seems to have acted as a touchstone for Royal Society investigations into the nature of phosphorescence[64]. From the perspective of modern science, Thomas Harriot is the more impressive character; from that of his immediate successors, however, the laurels must go to Bacon.

[60] The exception is the mathematical work *Artis analyticae praxis*, published in 1631 by Harriot's long-time friend and colleague Walter Warner.
[61] Tanner, 'Thomas Harriot as Mathematician: A Legacy of Hearsay'.
[62] All three books were in Robert Hooke's library, the second in the 1662 Amsterdam edition and the third under the title *Opuscula philosophica*; see Poole, Henderson and Yasifoglu, eds., *Hooke's Books*.
[63] Boyle, *New Experiments and Observations Touching Cold*, 421.
[64] For Royal Society activity in the area, see Golinski, 'A Noble Spectacle'. In the preface to his book on the subject, the *Aerial Noctiluca*, Robert Boyle distinguishes between 'artificial' phosphoruses and "Those that may be stil'd Natural, as Glow-worms, some sorts of rotten Wood and Fishes, and a few others", 269.

Devoting an entire chapter to a single philosopher facilitates the first goal of the thesis: it serves to emphasise their practical work in optics, a result that is, of course, more striking in some cases than in others. Practical optics is already a familiar aspect of the work of Robert Hooke and Isaac Newton. The same, however, cannot be said of Francis Bacon and Thomas Hobbes, albeit for different reasons. Bacon's practical activities have been the subject of some scholarly scrutiny in recent years, but his work in optics has hitherto received no significant attention. Hobbes's interest in optics, on the other hand, is generally well-known, but his practical activities in the field have not yet been subjected to any sustained discussion.

Devoting an entire chapter to a single philosopher is, however, an approach that comes into its own for the second goal of the thesis: it reveals something of the culture surrounding seventeenth-century work in optics, by allowing close attention to each thinker's polemical purposes. The chapter on Francis Bacon, for example, details his attempts to counter the work of an Italian contemporary, Bernardino Telesio. That on Thomas Hobbes describes his disagreements on optical matters with René Descartes. The chapter on Robert Hooke goes over his conflict with Isaac Newton. And that on Newton examines the same dispute, but from the other side.

As each chapter serves to emphasise an individual philosopher's use of practical work and to set it in a polemical context, each can stand alone for readers interested in that particular intellectual figure. Another result of dedicating an entire chapter to a single thinker, however, is the fact that it allows the identification of their audience. When viewed from this perspective, the four chapters come together to form a narrative about the changing nature of the audiences for practical activity as the century progressed.

Francis Bacon's principal investigation into the nature of light, the *Topica inquisitionis de luce et luminis*, was not published in his lifetime and does not appear to have circulated in manuscript: it seems, in fact, to have been intended primarily for himself. Thomas Hobbes's optical activity of the 1630s and 1640s was directed at a small network of trusted associates, the Cavendish circle, with whom he felt comfortable sharing his thoughts on the subject. Robert Hooke's work in the field had a larger group, the Royal Society, as its target audience. Finally, Isaac Newton published a book on optics, to considerable public acclaim.

When viewed as a narrative, then, the thesis has something to say about the increasingly public nature of natural philosophy in this period. In the seventeenth century, science became a communal, social enterprise. The process can be viewed as an aspect of the extremely broad shift that Jürgen Habermas has famously characterised as the rise of the 'public sphere'[65], although, as David Zaret has noted, Habermas himself does not have that much to say about the rise of public science[66].

The generation and promulgation of socially constructed 'matters of fact' is a theme running through some of Steven Shapin's work on seventeenth-century natural philosophy: in the conclusion to an essay published in 1984 on Robert Boyle's experiments with the air-pump, for example, he describes the "language of early Restoration experimental science" as "a public language" and continues: "the use of this public language was, in Boyle's work, essential to the creation of both the knowledge and the social solidarity of the experimental community. Trust and assent

[65] Habermas, *The Structural Transformation of the Public Sphere*.
[66] Zaret, 'Religion, Science and Printing in the Public Spheres'.

had to be won from a public that might crucially deny trust and assent"[67]. In the period immediately following the civil wars and interregnum, Shapin notes, questions of assent and dissent carried distinctly political overtones; he quotes Thomas Sprat's claim in *The History of the Royal Society* that the initial urge of the men who met in Oxford in the 1650s and later founded the Royal Society was "onely the satisfaction of breathing a freer air, and of conversing in quiet with one another, without being ingag'd in the passions, and madness of that dismal Age". The contemplation of nature, Sprat writes later in the work, "draws our mind off from past, or present misfortunes". It "gives us room to differ, without animosity" and "permits us, to raise contrary imaginations", without "any danger of a *Civil War*"[68].

If a strand in the increasingly public character of seventeenth-century natural philosophy involved the quest for assent and the desire properly to manage dissent, the material foregrounded in the following chapters highlights the ongoing presence of a raucous, ungentlemanly spirit of dispute. Matthew Hunter has recently highlighted the increasing scholarly interest in the "flagrant disregard for communal norms", the "outrageous, egregious behaviour" displayed by intellectual figures active in the second half of the seventeenth century[69]. He quotes a description of Restoration England – "a world of change and uncertainty, of sensational plots and conspiracies, of endless personal intrigue and manoeuvring, of widespread corruption and almost universal cynicism"[70] – and comments: "the Royal Society envisaged in recent historiography

---

[67] Shapin, 'Pump and Circumstance', 511.
[68] Sprat, *The History of the Royal Society*, G3^{r} and G4^{v}, quoted in Shapin, 'Pump and Circumstance', 506-7. The same theme is prominent in Shapin, *A Social History of Truth*, and Shapin and Schaffer, *Leviathan and the Air-Pump*.
[69] He quotes from Goldgar, *Impolite Learning*, 9, and references Hunter, *Science and Society* and *Establishing the New Science*; Johns, *The Nature of the Book*; Iliffe, '"In the Warehouse"' and 'Material Doubts'; and Gal, *Meanest Foundations and Nobler Superstructures*.
[70] Jones, *Country and Court*, 1.

appears not much better"[71]. Certainly, when it comes to optical activity, seventeenth-century English natural philosophers seem to have appreciated instruments and experiments for their weight in a culture characterised by conflict. The use of practical work could serve as a valuable means of persuading an audience that the ideas of a rival were wrong. Over the course of the century, that audience expanded from one man to the entire literate public.

[71] Hunter, *Wicked Intelligence*, 8.

Francis Bacon Dissolves Iron in Acid in the Dark

In a chapter published in the *Cambridge Companion to Bacon* in 1996, the great Bacon scholar Paolo Rossi asks himself what kind of a contribution Francis Bacon (1561-1626) made to modern science, observing that none of the great discoveries that have transformed human knowledge of the natural word (he lists heliocentrism, the principle of inertia and the circulation of the blood as examples) can be traced to him. Rossi's answer is that: "Bacon is one of the constructors – perhaps the greatest – of that which can be called a modern image of science". His work "concerns above all the function of science in human life, the ends and values that must characterise scientific knowledge; it concerns that which today we would call an ethics of scientific research; it concerns, finally, the ways in which this form of knowledge must present itself in comparison to the other forms of cultural life: poetry, history, religion, ethics, politics"[1]. Rossi's judgement reflects something of a consensus among Baconians and has found echoes in subsequent introductory studies by John Henry and Perez Zagorin[2]. Here, I am not suddenly going to attribute any great discoveries to Bacon. I am, however, concerned that too strong an emphasis on his articulation of 'a modern image of science' can result in neglect of his actual scientific practice: it can lead us to underestimate the time and energy that he devoted to investigating the natural world.

No-one has done more to explore Francis Bacon's thoughts about aspects of the natural world than Graham Rees. In a series of articles and book chapters, Rees has excavated his subject's conception of such things as the structure of the cosmos, the interior of the

[1] Rossi, 'Bacon's Idea of Science', 26.
[2] Henry, *Knowledge is Power*, 1, and Zagorin, *Francis Bacon*, 222.

Earth, the movement of the heavenly bodies, the winds and tides, and the role of 'spirits' in the generation and decay of plant and animal life[3]. In Rees's hands, however, Bacon's understanding of how the world works is largely a textual affair, with little relation to his actual experience of nature. In the introduction to his first essay on the subject, published in 1975, Rees writes that Bacon's cosmology "brings together kinematic principles derived from an Arab supporter of Aristotle, a dynamical theory partly adapted from the natural-magical tradition and, above all, a chemico-physical theory whose origins are to be found in Paracelsian thought"[4]. In his introduction to volume six of the *Oxford Francis Bacon*, published 21 years later, he writes in a similar vein: "The system was eclectic to a fault. It grew and matured as Bacon raided disparate traditions for attractive titbits which he refashioned as a curious hybrid which embodied some very peculiar alliances of ideas"[5].

More recent Baconians have extended Graham Rees's work on Bacon's conception of the natural world: in particular, Guido Giglioni has devoted a number of essays and book chapters, as well as a section of his book on Bacon, to the philosopher's thoughts about the 'appetites' of matter[6]. Unlike Rees, however, Giglioni is able to benefit from a rich corpus of scholarship on Bacon's practical activities, what Lisa Jardine has called his 'hands-on science'[7]. Much of this scholarship is concerned with Bacon's thoughts about what he referred to as 'experientia literata' (literate or informed experience).

[3] Rees, 'Bacon's Semi-Paracelsian Cosmology', 'Bacon's Semi-Paracelsian Cosmology and the Great Instauration', 'The Fate of Bacon's Cosmology', 'Matter Theory', 'Bacon on Verticity', 'Atomism and 'Subtlety'', 'Bacon and *spiritus vitalis*', and 'Bacon's Biological Ideas'. These studies are synthesised as 'Bacon's Speculative Philosophy' in Rees's introduction to *The Oxford Francis Bacon 6*, xxxvi-lxix.
[4] Rees, 'Bacon's Semi-Paracelsian Cosmology', 81.
[5] Rees, 'Introduction', in *The Oxford Francis Bacon 6*, xxxvii.
[6] Giglioni, 'Mastering the Appetites of Matter', 'How Bacon Became Baconian' and *Francesco Bacone*, 59-95. See also the articles collected in *Francis Bacon on Motion and Power*, edited with James A.T. Lancaster, Sorana Corneanu and Dana Jalobeanu.
[7] Jardine, 'Revisiting Rossi on Francis Bacon'.

Cesare Pastorino, for example, has described Bacon's experimental inquiry into specific gravities, recorded in his natural history of dense and rare[8]. Laura Georgescu has examined the experiments that feature in his natural history of the winds[9]. Likewise, Dana Jalobeanu has reconstructed the experiments with apples that were conducted as part of an investigation into the processes of maturation and putrefaction[10]. All three authors pay their debts to a seminal article by Lisa Jardine, first published in 1985, '*Experientia literata* or *Novum organum*?'[11].

The motivation underlying such work could be viewed as essentially 'philosophical' in character: the implicit starting-point in each case is an interest in the value that Bacon ascribed to knowledge derived from experimentation, rather than an interest in the value that he ascribed to knowledge about density, wind or putrefaction. This 'philosophical' approach can perhaps be exemplified by Peter Anstey's recent placement of Bacon alongside Robert Boyle and Robert Hooke as a theorist of "a representative early modern philosophy of experiment"[12].

Guido Giglioni has contributed an important article to the ongoing reconstruction of Bacon's 'philosophy of experiment'[13]. Elsewhere, however, he has focussed his attention more precisely on the *Sylva sylvarum*, a hotchpotch of natural historical information published shortly after Bacon's death that, in the seventeenth century, was his most reprinted work of natural philosophy[14]. For Giglioni, it is "the work where

[8] Pastorino, 'Weighing Experience'.
[9] Georgescu, 'A New Form of Knowledge'.
[10] Jalobeanu, 'Bacon's Apples'.
[11] Jardine, '*Experientia literata* or *Novum organum*?'.
[12] Anstey, 'Philosophy of Experiment', 104.
[13] Giglioni, 'Learning to Read Nature'.
[14] For a list of the printings of Bacon's works, see Gibson, *Bacon: A Bibliography* and *Supplement*. The printings of the *Sylva sylvarum* are listed in the former, xv. Only the *Essays* were reprinted more often; see xiii.

Bacon expounded [...] his views on the material appetites of nature, and did so not by writing in the abstract, but by describing and performing experiments aimed at disclosing the appetitive nature of matter"[15]. The approach adopted in this piece seems to be motivated by a fundamentally different question: Giglioni is not asking what kind of value Bacon ascribed to experimentation (in general), but what kind of value he ascribed to these experiments (in particular). His approach involves an examination of the role that the experiments contained in the *Sylva sylvarum* might be playing in the context in which they were performed and described in print. His approach, in short, could be thought of as less 'philosophical' and more 'historical'.

In what follows, I pursue a similar tack, although my subject-matter occupies a lower rung on the ladder from physics to metaphysics: rather than the somewhat abstract concept 'matter', I will be examining something that Bacon would have encountered on a daily basis: light. The first section of the chapter sets Bacon's work on light in the context of his life; it discusses the practical work that appears in the natural histories written after his fall from political power in 1621. The second introduces his conviction that light is distinct from heat, an idea that, as I show, should be thought of as a stance in a contemporary debate. Finally, the third examines his use of information gained from instruments and experiments, which I view as a tool in a dispute about the nature of light. The Bacon who emerges from my analysis is, in one obvious sense, a new one: his work on light has not yet attracted any significant scholarly attention. What follows, however, contributes to Guido Giglioni's image of a philosopher whose ideas about the value of practical science may have been rooted as much in immediate, specific conceptions of nature as they were in abstract, epistemological reflections.

[15] Giglioni, 'Mastering the Appetites of Matter', 149.

A "high kind of natural magic": Practical Natural History

In 1621, the Lord Chancellor, Francis Bacon, was forced to confess that he had accepted bribes[16]. Barred from Parliament and banished from court, he spent much of the remaining five years of his life at his estate in Gorhambury, near St Albans[17]. In their biography, Lisa Jardine and Alan Stewart write: "Forced into seclusion, he at last found time to focus his attention on the intellectual projects from which his public commitments had previously distracted him"[18]. These intellectual projects included the preparation of his principal work on light, the *Topica inquisitionis de luce et lumine*, although his major natural philosophical occupation was a series of natural histories, works that have generally been the object of less study than other parts of his writing, although this neglect has of late been somewhat remedied[19].

The recent increase in the scholarly attention paid to Bacon's natural histories may, in part, be the result of the burgeoning interest, mentioned in the introduction to this chapter, in his references to practical activity, many of which appear in these texts. Ahead of any discussion of his work on light, it seems worth establishing the context in which it was written: in particular, the aim of this section is to emphasise the time and energy that he was devoting in these years to a particularly practical form of natural history. Indeed, it is difficult not to raise a biographical suggestion: although, as we

---

[16] For a description of the case, see Jardine and Stewart, *Hostage to Fortune*, 444-69. For Bacon's confession, see Spedding, ed., *The Letters and the Life*, vol. 7, 252-62.
[17] This period of Bacon's life is described in Jardine and Stewart, *Hostage to Fortune*, 473-501.
[18] Jardine and Stewart, *Hostage to Fortune*, 473
[19] For recent work, see the collection of articles published in a special issue of *Early Science and Medicine* 17, no. 1-2 (2012), as well as Giglioni, 'Mastering the Appetites', Jalobeanu, 'The Philosophy of Bacon's Natural History' and *The Art of Experimental Natural History*, and Manzo, 'Probability, Certainty and Facts'. Doina-Christu Rusu and Christoph Lüthy's 'Extracts from a Paper Laboratory' was published after the completion of this chapter.

shall see, practical natural history was not a new pursuit for Bacon in the 1620s, it may well have gained new vigour from his enforced retirement.

In their biography, Jardine and Stewart quote a list of writings dating to this period, which was included in the *Life of Francis Bacon*, written by Bacon's chaplain and *de facto* literary executor, William Rawley, and published in 1657[20]. An obviously noteworthy feature of the list is the number of items referred to as natural histories, given the fact that neither of the natural philosophical works published before his downfall could be described in this way. In the opening to the *Advancement of Learning*, published in 1605, he writes that the two subjects of the book will be the excellence of learning and the current state of human knowledge[21]. Meanwhile, although the *Novum organum* – the principal text in a 1620 volume entitled the *Instauratio magna* – features a considerable amount of information about the natural world, it is framed as a corrective to contemporary works of logic[22].

In 1622, by contrast, the year after Bacon's banishment, he published an introduction to natural history, a natural history of the winds, and the prefaces to five other titles that he intended to issue over the coming months[23]. Of these, the *Historia vitæ & mortis* appeared the following year, the *Historia densi & rari* reached an advanced stage in manuscript and was published posthumously, and the *Historia gravis & levis* is described as lost in William Rawley's list. The introduction to the *Sylva sylvarum*, published in 1627 shortly after Bacon's death, suggests that this work should also be

[20] Rawley, *Life of Francis Bacon*, 9-10. The passage is quoted in Jardine and Stewart, *Hostage to Fortune*, 476. For Rawley's life and career, see Stewart, 'Rawley, William'.
[21] Bacon, *Advancement of Learning*, 5.
[22] Bacon, *Novum organum*, 52-54 and 442. For a discussion of the work's relationship with contemporary works of logic, see Jardine, *Discovery and the Art of Discourse*, 17-75.
[23] Bacon, *Historia naturalis et experimentalis*, *Historia ventorum*, and *Aditus ad titulos*.

thought of as a natural history; Rawley writes: “the scope which his lordship intendeth, is to write such a Natural History as may be fundamental to the erecting and building of a true philosophy”[24]. A comment within the text itself, meanwhile, frames it as a particularly practical exercise in the genre: “the writing of our *Sylva sylvarum* is (to speak properly) not natural history, but a high kind of natural magic. For it is not a description only of nature, but a breaking of nature into great and strange works”[25].

The turn to natural history cannot, of course, be attributed solely to the downturn in Bacon’s political fortunes. The 1620 volume opens with an overview of his six-part project to reform learning, the ‘Great Instauration’. In this overview, the *Distributio operis*, he assigns natural history to part three of the project and describes it as the “foundations for the building up of philosophy”[26]. A similar comment appears in the *Parasceve, ad historiam naturalem, et experimentalem*, which follows the *Novum organum* in the same volume and features an introduction to the writing of natural history and a catalogue of proposed studies[27]. The title of this work and a number of references to experimentation within it suggest that a turn to practical work is also not wholly attributable to his change in circumstances[28]. It is, however, perhaps worth considering the idea that his enforced retirement was the prompt for a more active involvement in hands-on activity than would otherwise have been the case.

---

[24] Rawley, ‘To the Reader’, in Bacon, *Sylva sylvarum*, 335-7, at 335.
[25] Bacon, *Sylva sylvarum*, 378. For Bacon’s conception of natural magic, see Rossi, *From Magic to Science*, 1-35; Rusu, ‘From Natural History to Natural Magic’, and Weeks, ‘Bacon’s Science of Magic’.
[26] *ad condendam Philosophiam fundamentalis*, Bacon, *Distributio operis*, 36, translated on 37. For an overview of the Great Instauration, see Graham Rees’s introduction to *The Oxford Francis Bacon 6*, xvii-xix. For the place of natural history, see his introduction to *The Oxford Francis Bacon 12*, xvii-xviii.
[27] He writes: “Ea est Descriptio & Delineatio Historiæ Naturalis & Experimentalis, eius generis, quæ sit in Ordine ad Condendam Philosophiam” (“This is a description and delineation of a natural and experimental history which may serve for the building up of philosophy”); see Bacon, *Parasceve*, 450, translated on 451.
[28] For references to experimentation in the *Parasceve*, see 454, 461 and 462-4.

In a letter to the Italian natural philosopher Redemptus Baranzano of June 1622, Bacon certainly sounds proactive: "A Natural History out of which philosophy may be built is (as you also observe) what I desire before anything else; nor shall I be wanting to the work, so far as in me lies. I wish I may have fit assistants"[29]. Given his position as a member of the English aristocracy, it seems unlikely that Bacon's desire not to be "wanting to the work" extended to handling instruments or conducting experiments personally[30]. More probably he provided directions, while William Rawley co-ordinated a team comprised of members of the household, who carried out the labour. These may be the "assistants" referred to in the letter, although this could also be a reference to those, such as Baranzano, whom Bacon hoped would be inspired to follow his lead and prepare their own natural histories[31].

Such an enthusiastic attitude seems to have waned over the following years. In the introduction to the *Sylva sylvarum*, Rawley sounds a comparatively weary tone: "I have heard his lordship speak complainingly, that his lordship (who thinketh he deserveth to be an architect in this building) should be forced to be a workman and a labourer, and to dig the clay and burn the brick; and more than that, (according to the hard condition of the Israelites at the latter end) to gather the straw and stubble over all the fields to burn the bricks withal"[32]. The complaint could refer to the lack of assistance provided

[29] *Historiam naturalem ad condendam philosophiam (ut et tu mores) ante omnia prœopto, neque huic rei deero, quantum in me est; utinam habeam et adjutores idoneos*, Francis Bacon to Redemptus Baranzano, in Spedding, ed., *The Letters and the Life*, vol. 7, 375-7, translated on 377-8n. The quote is from 376, translated on 377n.
[30] Lisa Jardine makes this point in 'Revisiting Rossi', 64.
[31] Bacon expresses the hope that his work will inspire others in the *Parasceve*, 450, and in the dedicatory epistle to the *Historia naturalis et experimentalis*, 4. Baranzano appears to have offered to write a natural history of the heavens; see Bacon to Baranzano, in Spedding, ed., *The Letters and the Life*, vol. 7, 376.
[32] Rawley, 'To the Reader', in Bacon, *Sylva sylvarum*, 336.

in the form of the histories that Bacon hoped others would write, but it is tempting to think more literally and speculate that his penury in the years following his fall from grace may have led to a lack of staff, forcing him into a more active involvement in practical work than he would perhaps have preferred[33].

Whatever the case may be, two collections of notes dating from the final years of Bacon's life depict a natural philosopher intimately involved in the finer points of active investigation. The first, published in 1679, features, to take just one example, the results of an experiment that involves weighing various items – a sovereign, a bladder, a sponge *etc*. – in and out of water[34]. Meanwhile, the second, which is now lodged in the British Library, contains draft lists of such things as places to try storing beer and apples, which, as Graham Rees has highlighted, appear to have served as the basis for experiments that are reported in the *Sylva sylvarum*[35].

By 1625, perhaps as a result of this level of personal involvement, Bacon seems to have come to the conclusion that his achievements in the field of natural history were as nothing compared to the work that remained to be done. In a letter to another Italian philosopher, Fulgenzio Micanzio, he sounds a despairing tone: "As for the third part [of the Great Instauration], namely, the 'Natural History', that is plainly a work for a King or Pope, or some college or order: and cannot be done as it should be by a private man's industry"[36]. The reference here to a "college or order" prompts thoughts of

[33] For a discussion of Bacon's penury in this period, see Jardine and Stewart, *Hostage to Fortune*, 477-8.
[34] Bacon, *Physiological and Medical Remains*, 819-21.
[35] Rees, 'An Unpublished Manuscript', 394-412; the lists appear, together with his notes linking the contents to the *Sylva sylvarum*, on 405 and 406. The relevant sections of the *Sylva sylvarum* are 444, 446-7, 475-6 and 485-6. For the relationship between the two collections of notes, see Rees's introduction to 'An Unpublished Manuscript', 377-94, at 380; he dates both, 379, to 1623-6.
[36] *Quod ad tertiam partem Instaurationis attinet, Historiam scilicet Naturalem, opus illud est plane regium aut papale, aut alicujus collegii aut ordinis; neque privata industria pro merito perfici potest,*

Solomon's House, an intellectual brotherhood also referred to as the 'College of the Six Days' Works' in Bacon's utopian narrative, the *New Atlantis*, which was first published alongside the *Sylva sylvarum* in 1627[37]. Without wishing to sideline the complexities involved in the production of a work of fiction, it seems worth using the practical activity conducted by Solomon's House as a means of approaching the comparable work that Bacon was engaged in at the same time[38].

In the *New Atlantis*, the Father of Solomon's House provides the narrator with an overview of the society, the second and by far the longest section of which covers what he calls the "preparations and instruments we have for our works"[39]. It begins: "We have large and deep caves of several depths [...] And we use them for all coagulations, indurations, refrigerations, and conservations of bodies [...] We use them also sometimes, (which may seem strange,) for curing of some diseases, and for prolongation of life in some hermits that choose to live there"[40]. With regard to Bacon's work of the period, these comments are most obviously reminiscent of the reports in the *Sylva sylvarum* of experiments involving the preservation of fruit by burial[41], although the behaviour of metals underground is also a subject of interest in the *Historia densi & rari*[42]. Meanwhile, the reference to the medicinal properties of caves is suggestive of a comment in the *Historia vitæ & mortis*: "Life in dens and caves where the air does not receive the Sun's rays can contribute to long life"[43].

Bacon, 'Epistola ad Fulgentium', in Spedding, ed., *The Letters and the Life*, vol. 7, 531-2, translated on 533n. For the background to Bacon's correspondence with Micanzio, see Malcolm, *De Dominis*, 49-50.
[37] Solomon's House is referred to as the 'College of the Six Days' Works' in Bacon, *New Atlantis*, 146.
[38] Dana Jalobeanu has also considered the descriptions of Solomon's House within the context of Bacon's program for natural history; see 'The Philosophy of Bacon's Natural History', 20-2.
[39] Bacon, *New Atlantis*, 156-66, at 156; the section is 156-64.
[40] *Ibid.*, 156-7.
[41] Bacon, *Sylva sylvarum*, 467.
[42] Bacon, *Historia densi & rari*, 54-6 and 166.
[43] Vita *in* Antris & Speluncis, *vbi* Aer *non recipit* Radios Solis, *possit facere ad Longæuitatem*, Bacon, *Historia vitæ et mortis*, 272, translated on 273. Graham Rees translates "recipit" as "admit".

The Father of Solomon's House moves on to the society's horticultural activities: "We have also large and various orchards and gardens […] In these we practise likewise all conclusions of grafting and inoculating [...] And we make (by art) in the same orchard and gardens, trees and flowers to come up earlier or later than their seasons; and to come up and bear more speedily than by their natural course they do"[44]. The obvious comparison, again, is with the *Sylva sylvarum*, in particular with the material in the fifth section (referred to as a 'century')[45]. Bacon devotes a passage to extolling the benefits that would accrue from being able to cross-breed plants[46], a draft of which appears in the manuscript notes in the British Library[47]. He discusses various forms of compost, praising the qualities of horse dung[48], and observes: "To make roses or other flowers come late, it is an experiment of pleasure [...] And indeed the November-rose is the sweetest, having been less exhaled by the sun"[49].

The Father of Solomon's House proceeds to discuss marvels involving sound: "We have also sound-houses, where we practise and demonstrate all sounds, and their generation [...] We represent small sounds as great and deep; likewise great sounds extenuate and sharp; we make divers tremblings and warblings of sounds, which in their original are entire [...] We have also divers strange and artificial echos, reflecting the voice many times, and as it were tossing it: and some that give back the voice louder than it came; some shriller, and some deeper"[50]. Once again, the obvious point of comparison is with the *Sylva sylvarum*. The second century and a considerable section

[44] Bacon, *New Atlantis*, 158.
[45] The *Sylva sylvarum* is divided into ten 'centuries'; the fifth is 475-500. Other comments about plants appear in the sixth, 501-27, and in the first half of the seventh, 528-62, at 528-50. For Bacon's work on plants, see Rusu, 'From Natural History to Natural Magic', 139-77.
[46] *Ibid*., 492-3.
[47] Rees, 'An Unpublished Manuscript', 411.
[48] Bacon, *Sylva sylvarum*, 475-9; horse dung is praised on 475.
[49] *Ibid*., 479.
[50] Bacon, *New Atlantis*, 162-3.

of the third are dedicated to acoustic observations[51], evidence for the planning of which is again visible in the collection of manuscript notes in the British Library[52]. Towards the beginning of the second century, Bacon provides an overview of the current, to his mind deplorable, state of music theory[53], but he concludes optimistically: “these and the like conceits, when men have cleared their understanding by the light of experience, will scatter and break up like mist”[54].

Bacon’s practice, inescapably, falls far short of the wonders that the members of Solomon’s House are, by the Father’s account, able to produce. The latter, however, stand as indications of the kinds of instruments and experiments that he thought desirable and towards which, in some cases, he was working. The turn towards practical natural history had been set in motion before his fall from grace, but it is certainly difficult not to think that his involvement in the hands-on work of this period was closer than it would have been, had he maintained his political status.

This is a general conclusion and, in making it, I have been able to give little more than a flavour of Bacon’s practical activities of the period. I have not, for example, yet mentioned the Father of Solomon’s House’s description of the society’s means of manipulating light: “We have also perspective-houses, where we make demonstrations of all lights and radiations; and of all colours [...] We have also glasses and means to see small and minute bodies perfectly and distinctly; as the shapes and colours of small bodies and worms, grains and flaws in gems, which cannot otherwise be seen;

---

[51] The second century is Bacon, *Sylva sylvarum*, 385-413; the relevant section of the third is 414-36.
[52] Rees, ‘An Unpublished Manuscript’, 410.
[53] Bacon, *Sylva sylvarum*, 390-3. For Bacon’s work on music, see Gouk, ‘Music in Bacon’s Natural Philosophy’.
[54] Bacon, *Sylva sylvarum*, 394.

observations in urine and blood, not otherwise to be seen"[55]. As these comments suggest, and as will be seen in the remainder of this chapter, one of the subjects attracting Bacon's practical attention in these years was light.

[55] Bacon, *New Atlantis*, 161-2.

“[T]he tendrils of errors […] can be mowed and cut down”: The Nature of Light[56]

Bacon’s work on light has hitherto been the subject of almost no sustained discussion, a fact that provides this section of the thesis with a simple *raison d’être*[57]. Although his thoughts undoubtedly owe something to curiosity, his principal conclusion – that light is distinct from heat – should be seen, as I will show, primarily as the product of an engagement with the work of an Italian contemporary, Bernardino Telesio. The latter has typically been viewed in Bacon scholarship as a source from which he drew positively for ideas about such things as the structure of the universe and the relationship between ageing and spirits[58]. Jean-Marie Pousseur, by contrast, has identified Bacon’s disagreement with the Telesian association of heat, light, tenuity and motion, but his essay does not refer to Bacon’s major work on light, the *Topica inquisitionis de luce et lumine*, and, perhaps as a result, it does not state as forcefully as it could the implications for our understanding of his logical method[59].

It is tempting to think of the method, often referred to as ‘Baconian induction’, as a disinterested tool for the advancement of knowledge; a number of descriptions, sometimes involving philosophically-minded critiques, have presented a process that is

[56] The material in this section forms the basis for Everest, ‘Francis Bacon’s Method’.
[57] The exception is the early nineteenth-century Savoyard conservative Joseph de Maistre; see *Examen de la philosophie*, 203-22. He writes: “Nouvelle preuve démonstrative que non-seulement Bacon n’a pas avancé la science mais que, si malheureusement il était lu, compris et suivi, il l’aurait tuée ou retardée sans bornes” (“This is a new demonstrative proof that not only did Bacon not advance science, but that, if he had been read, understood, and followed, he would have killed or retarded it without limits”), 210, translated by Richard Lebrun, 105.
[58] For comments in this vein, see Gemelli, *Aspetti dell’atomismo classico*, 104-22; Giglioni, ‘Mastering the Appetites’, 157-63; Rees, ‘Bacon’s Semi-Paracelsian Cosmology’, 92-3, ‘Bacon on Verticity’, 205, and ‘Bacon’s Biological Ideas’, 304; and Walker, ‘Spirits in Francis Bacon’.
[59] Pousseur, ‘Bacon, a Critic of Telesio’.

abstracted from his actual use of it in investigating features of the natural world[60]. Of course, there is no doubting his conception of the value that an effective method of discovery would have for the desired instauration of the sciences[61]. An examination of his work on light, however, suggests that the method may also have been valuable for the role that it could play in a particular scientific dispute about a particular aspect of nature: it helped to make the case that Telesio's thoughts about light were wrong.

The most immediately striking element of Bacon's comments about light is how little they owe to the tradition of geometrical optics, known in Latin works of the period as 'perspectiva'[62]. In a Latin translation and expansion of the earlier *Advancement of Learning,* entitled the *De augmentis scientiarum* and published in 1623, he writes:

> That no due investigation has been made concerning the Form of Light (especially as men have taken great pain about perspective [*Perspectiva*]) may be considered an astonishing piece of negligence. For neither in perspective, nor otherwise has any inquiry been made about Light which is of any value. The radiations of it are handled, not the origins[63]

Geometrical optics, Bacon suggests here, provides a means of understanding the behaviour of light – its "radiations" – but it offers little insight into what light actually

[60] The classic philosophically-minded critic is Karl Popper; see, for example, *The Logic of Scientific Discovery*, 278-9, and *Conjectures and Refutations*, 12-7. Similarly abstract accounts, however, appear in Hesse, 'Bacon's Philosophy of Science', and Malherbe, 'Bacon's Method of Science'.
[61] For a sense of the importance that Bacon ascribed to method, see Jardine, *Discovery and the Art of Discourse*, 1-132.
[62] For an overview of this tradition, see Lindberg, *Theories of Vision*, 104-208.
[63] *De Forma Lucis quod debita non facta fuerit inquisitio (præsertim cum in Perspectiva strenue elaborarint homines), stupenda quœdam negligentia censeri possit. Etenim nec in Perspectiva nec alias aliquid de Luce quod valeat inquisitum est. Radiationes ejus tractantur, origines minime,* Bacon, *De augmentis scientiarum*, 612, translated in vol. 4, 403.

is. He continues: "But it is the placing of perspective among the mathematics that has caused this defect, and others of the kind; for thus a premature departure has been made from Physics"[64]. This is, then, a statement about the place of the disciplines. The mathematical approach, for Bacon, involves an over-hasty abstraction from what should be the first object of philosophical inquiry: the nature of light.

Yet, progress in physics, the discipline that really ought to be concerned with what light is, seems also to have been a disappointment: "Again the manner in which Light and its causes are handled in Physics is somewhat superstitious, as if it were a thing half way between things divine and things natural; insomuch that some of the Platonists have made it older than matter itself; asserting upon a most vain notion that when space was spread forth it was filled first with light, and afterwards with body; whereas the Holy Scriptures distinctly state that there was a dark mass of heaven and earth before light was created"[65]. In an editorial footnote, James Spedding suggests that this accusation of superstition is directed at the physician and occult philosopher Robert Fludd[66]. A more likely target, however, is to be found in Francesco Patrizi's *Nova de universis philosophia*, which Graham Rees has identified as a source for comments in works dating to earlier in Bacon's career[67]. In any case, the subsequent call to arms is

[64] *Sed collocatio demum Perspectivæ inter Mathematica hunc ipsum defectum, et alios similes, peperit; quia a Physicis præmature discessum est*, Bacon, *De augmentis scientiarum*, 612, translated in vol. 4, 403.
[65] *Tractatio autem de Luce et causis ejus in Physicus rursus superstitiosa fere est, tanquam de re inter divina et naturalia media; adeo ut quidam ex Platonicis eam Materia ipsa antiquiorem introduxerint: cum enim spatium esset difflatum, id primum lumine, postea vero corpore impletum fuisse, vanissimo commente asseruerunt; quando tamen Scripturæ Sacræ massam cœli et terræ tenebrosam, ante lucem creatam, diserte posuerint*, Bacon, *De augmentis scientiarum*, 612, translated in vol. 4, 403.
[66] Spedding suggests that the target is Fludd, *Utriusque cosmi maioris*; see 612n. For Fludd's life and work, see Maclean, 'Fludd, Robert'.
[67] See the chapter 'De primævo lumine', in the section 'Pancosmia', in Patrizi, *Nova de universis philosophia*, Aa1^{v}-Aa3^{r}. Bacon refers to the section, although not to this chapter, in the *Descriptio globi intellectualis*, 132 and 158-160. Graham Rees also sees its influence elsewhere in the *Descriptio globi intellectualis* and in the contemporary *De fluxu et refluxu maris*; see his commentaries, 376, 394 and 403. In his introduction to *The Oxford Francis Bacon 6*, he dates the composition of *Descriptio globi intellectualis* to *c*.1612 and views the *De fluxu et refluxu maris* as contemporary; see xix and

rooted in a physics shorn of such vain notions: “Now men ought to have sunk their speculations for awhile, and inquired what that is which is common to all lucid bodies; in other words, into the Form of Light”[68].

Bacon returned to light in the *Topica inquisitionis de luce et lumine*, written in 1625 during his enforced retirement at Gorhambury, but not published in his lifetime[69]. The title draws on a traditional distinction made in optical works of the period, between ‘lux’ and ‘lumen’, with the first term referring to the luminous quality of a source of light and the second to the light emitted by it and perceived by the observer[70]. Bacon’s adherence to the traditional division is, however, not particularly rigid; in the *Topica inquisitionis*, in fact, the word ‘lumen’ appears only once[71]. The work is brief and reads very much like a draft, in which cursory observations have been placed together under obvious headings, such as “*Colours of light”* and “*Reflections of light*”[72]. There is not a great deal of similarity with the contemporary and comparably named *Historia & inquisitio de animato & inanimato* and *Inquisitio de magnete*[73], but an immediately notable feature of the text is the extent to which the first three sections echo the

xxiv. For an overview of Bacon’s thought on Patrizi, see Whitaker, ‘Francesco Patrizi and Francis Bacon’. For Neoplatonic optics, see Lindberg, ‘The Genesis of Kepler’s Theory’; Patrizi appears at 28-9.

[68] *Debuerant autem homines contemplationes suas submittere paulisper, et quid sit Corporibus omnibus Lucidis commune inquirere, tanquam de Forma Lucis*, Bacon, *De augmentis scientiarum*, 612, translated in vol. 4, 403.

[69] Rees dates the work’s composition to 1625 in his introduction to *The Oxford Francis Bacon 13*, xxvii.

[70] Bacon describes the distinction in the *Descriptio globi intellectualis*, 152-4 (my thanks to James Lancaster for drawing this reference to my attention). The terms also appear in the works of Francesco Patrizi and William Gilbert, among other contemporaries of Bacon; see Graham Rees’s commentary on the *Topica inquisitionis*, 333-4.

[71] Bacon, *Topica inquisitionis*, 254. In his commentary, Graham Rees notes a variant reading of ‘luminis’ for ‘lucis’ in the title “*Reflexiones Lucis*”, on 248; see 333.

[72] Colores Lucis; Reflexiones Lucis, Bacon, *Topica inquisitionis*, 246 and 248, translated on 247 and 249.

[73] Rees dates the composition of the works, respectively, to 1622 and 1625 in his introduction to *The Oxford Francis Bacon 13*, xxvii.

terminology and structure deployed in the investigation into heat that appears in Bacon's earlier work on method, the *Novum organum*.

In Bacon's overview of the Great Instauration, the *Distributio operis*, he assigns the method to part two[74]. His work on method, the *Novum organum*, is itself in two books, with the investigation of heat appearing towards the beginning of the second. It is introduced as a case-study, the subject-matter having apparently been selected at random: "Let us take the investigation of the form of heat", he writes, "by way of example"[75]. The inquiry into light in the *Topica inquisitionis*, like that into heat in the *Novum organum*, begins with a "*Table of presence*", a "*Table of absence in proximity"*, and a "*Table of degrees*". These tables bring together instances of things that emit light, things that do not but are similar to things that do, and things that do to varying degrees[76]. The arrangement of material in this format prompts Graham Rees to assign the *Topica inquisitionis* to part four of the Great Instauration[77]. The aim of part four is described in the *Distributio operis*: "to set out examples of investigating and discovering according to my plan and way". It is, Bacon concludes, "really nothing other than the application of the second part in detail and at large"[78].

[74] Bacon, *Distributio operis*, 28.
[75] *Exempli gratiâ: In Inquisitione de Formâ Calidi*, Bacon, *Novum organum*, 216, translated on 217.
[76] Tabula præsentiæ; Tabula absentiæ in proximo; Tabula graduum, Bacon, *Topica inquisitionis*, 244 and 246, translated on 245 and 247. For the relevant sections in the *Novum organum*, see 216-8, 220-36 and 236-52. They are described as "*Tabulam Essentiæ & Præsentiæ*" ("*Table of Essence and Presence*"), "*Tabulam declinationis*, siue *Absentiæ in proximo*" ("*Table of divergence* or *Absence in proximity*"), and "*Tabulam Graduum* siue *Tabulam Comparatiuæ*" ("*Table of Degrees* or *Comparative Table*"), on 218, 220 and 236, translated on 219, 221 and 237. For an overview of the function of the tables, as they appear in the *Novum organum*, see Graham Rees's introduction to *The Oxford Francis Bacon 11*, lxxii-lxxv.
[77] Rees, 'Introduction', in *The Oxford Francis Bacon 13*, xxiv-xxv.
[78] *Exempla proponantur inquirendi & inueniendi, secundùm nostram rationem ac viam*; *reuerà nil aliud est, quam Secundæ Partis applicatio particularis & explicata*, Bacon, *Distributio operis*, 42, translated on 43.

In the context of the dismissive comments in the *De augmentis scientiarum*, the approach to light in the *Topica inqusitionis* initially seems relatively straightforward. Bacon postpones geometrical optics and ignores contemporary work in physics, applying instead his own logical method, as he had exemplified it in the *Novum organum*. In this interpretation, the investigation into light, like the earlier one into heat, is simply a case-study: it is valuable as a demonstration of the progress that can be made by means of the method, rather than for any specific conclusions.

Structure and terminology are not, however, the only links between the *Novum organum* and the *Topica inquisitionis*: there is also a significant overlap in content, with many of the instances that feature in the table of presence in the later work also appearing in the table of absence in proximity in the earlier one[79]. Both, to take just a couple of examples, feature "sea spray dashed and scattered"[80], as well as "sugar when it is being scraped and broken"[81]. Perhaps the most arresting comparison involves the following comment from the *Novum organum*: "And not so many years ago it was observed and almost taken as a miracle that a certain girl's apron sparkled on slight movement or friction, the result perhaps of the alum or salts used to dye it sticking rather thickly, and forming a crust cracked by the friction"[82]. A strikingly similar

[79] Graham Rees highlights some of this overlap in his commentary on the *Topica inquisitionis*, 332 and 333.

[80] *rores aquæ salsæ percussæ & sparsæ*, Bacon, *Topica inquisitionis*, 244, translated on 245. In the *Novum organum* he writes: "Aqua Marina & salsa, noctù interdùm inuenitur remis fortitèr percussa coruscare" ("we find that sea and salt water sparkles when oars come down hard on it at night"), 226, translated on 227.

[81] *saccharum inter scalpendum & frangendum*, Bacon, *Topica inquisitionis*, 244, translated on 245. In the *Novum organum* he writes: "Saccharum omne, siue Conditum (vt vocant) siue simplex, modò sit durius, in tenebris fractum aut cultello scalptum coruscare" ("all sugar, be it refined (as they call it) or raw, so long as it is hard, sparkles in low light when broken or scraped with a knife"), 226, translated on 227.

[82] *Atque paucis abhinc annis, notissimum est, & pro miraculo quasi habitum, Gremiale cuiusdam Puellæ paulò motum aut fricatum coruscâsse: quod fortassè factum est ob alumen aut sales, quibus gremiale tinctum erat, paulò crassiùs hærentia & incrustata, & ex fricatione fracta*, Bacon, *Novum organum*, 226, translated on 227.

observation appears in the *Topica inquisitionis*: “recently a certain woman’s stomacher was found to glitter, but only when it was rubbed; now this had been dyed with a green containing alum, and it crackled a bit when it glittered”[83]. The example is clearly the same, although the ‘certain girl’ appears to have grown up in Bacon’s mind by the time she became a ‘certain woman’, five years later.

The overlap in the content of the two works prompts the thought that the selection of light as a subject for investigation may not have been as arbitrary as it first appears. Perhaps Bacon was simply recycling material that had struck him[84]. Or perhaps he was looking to clarify his understanding of the relationship between light and heat.

Before introducing the investigation into heat in the *Novum organum*, Bacon describes the intended object of discovery: “The work and aim of human knowledge is to discover (and the following are the terms which I possess that come closest to what I mean) the form, or true difference, or *natura naturans,* or source from which a given nature arises”[85]. The three tables – of presence, absence in proximity and degrees – are accordingly followed by “An Example of the *Exclusive* operation”, in which various candidates for the ‘form’ of heat, including light and tenuity, are rejected[86]. The exclusive operation is then followed by provisional conclusions, the “*First Vintage*”,

[83] *ventrale cujusdam fœminæ nuper inventum est, quod micaret, sed inter fricandum; erat autem tinctum in viridi, atque tincturam illam ingreditur alumen, & crepabat nonnihil cum micabat*, Bacon, *Topica inquisitionis*, 244, translated on 245.
[84] For Bacon’s habit of recycling his material, see Everest, ‘Bacon’s Habit’.
[85] *Datæ autem Naturæ Formam, siue Differentiam veram, siue Naturam naturantem, siue Fontem emanationis (ista enim vocabula habemus, quæ ad indicationem rei proximè accedunt) inuenire, Opus & Intentio est humanæ Scientiæ,* Bacon, *Novum organum,* 200, translated on 201. For an overview of the Baconian notion of ‘form’, see Pérez-Ramos, *Bacon’s Idea of Science*, 63-132.
[86] *Exemplum Exclusivæ*, Bacon, *Novum organum*, 256-60, at 256, translated on 257.

according to which the form of heat is "motion and nothing else"[87]. The *Topica inquisitionis* offers no comparable statement about the form of light, but a discussion of light's 'kinsfolk' provides a hint as to things that it is not: "As far as its generation is concerned, light has kinship with three things in the main: heat, tenuity and motion. Note therefore their marriages and divorces in relation to light, and the stages of their marriages and divorces"[88]. The subject of the comment is the similarity of these four things, what Bacon calls their 'kinship', but there is an implicit understanding that they are different, being capable, as he assumes, of 'divorce'.

A statement of the differences between this foursome appears in a description of what Bacon refers to as "*Instances of Divorce*"[89], one item in the long list of so-called "*Instances with Special Powers*" that follows the provisional conclusions about heat in the *Novum organum*[90]. Bacon provides an example of how the special powers in this class of instance could be utilised: "let the natures under investigation be those four which *Telesius* regards as a *Brotherhood* and, so to speak, room mates, namely hot, lucid, tenuous, and mobile or ready for motion. Yet we can find many *Instances of Divorce* among them. For air is tenuous and adapted to motion but not hot or lucid; the Moon is lucid but without heat; boiling water is hot but without lumen; the motion of

[87] Vindemiato prima; *Motus, & nihil aliud*, Bacon, *Novum organum*, 262-72; both quotes are from 262, translated on 263. For the function of the first vintage, see Graham Rees's introduction to *The Oxford Francis Bacon 11*, lxxv-lxxvi.
[88] *Cognationem maxime habet lux cum tribus rebus (quatenus ad generationem lucis): calore, tenuitate & motu. Videndum igitur de conjugiis & divortiis eorum, erga lucem, atque eorundem conjugiorum & divortiorum gradibus*, Bacon, *Topica inquisitionis*, 252-6, at 252, translated on 253.
[89] Instantias Diuortij, Bacon, *Novum organum*, 338-40, at 338, translated on 339.
[90] Prærogatiuis Instantiarum, Bacon, *Novum organum*, 272-446, at 272, translated on 273. For an overview of the instances with special powers, see Graham Rees's introduction to *The Oxford Francis Bacon 11*, lxxvii-xcii.

an iron needle on a versorium is swift and agile but subsists in a cold, dense and opaque body; and many other examples of the kind"[91].

In the light of these comments, the investigation in the *Topica inquisitionis* starts to look less like a case-study for the effectiveness of Bacon's method and more like an attempt to demonstrate the distinctiveness of light from heat, tenuity and motion. Meanwhile, the passage in the *Novum organum* suggests that the demonstration of this distinctiveness may have been aimed at a specific target, one originating in the work of the contemporary Italian natural philosopher Bernardino Telesio.

In the *De rerum natura*, the final version of which was published in 1586, Bernardino Telesio describes two fundamental principles of nature, warmth and cold, the first located in the sun and the second in the earth. In his cosmology, light is not distinct, but, alongside tenuity and motion, is one of the "faculties" of the Sun[92]. A lengthy and informed discussion of the Telesian worldview appears in Bacon's work, the *De principiis atque originibus*, which was probably written in or shortly after 1612, but not published in his lifetime[93]. The piece is ostensibly a natural philosophical interpretation of myths involving Cupid, but can easily be read as an extended critique of the ideas

---

[91] *Exempli gratia: sint Naturæ Inquisitæ, quatuor Naturæ illæ, quas* Contubernales *vult esse* Telesius, *& tanquàm ex eâdem Camerâ: viz. Calidum, Lucidum, Tenue, Mobile siue promptum ad Motum. At plurimæ inueniuntur* Instantiæ Diuortij *inter ipsas. Aër enim Tenuis est & habilis ad Motum, non Calidus aut Lucidus: Luna Lucida, absque Calore; Aqua feruens, Calida absque Lumine; Motus Acûs ferreæ super Versorium, pernix & agilis, & tamen in Corpore Frigido, Denso, Opaco; & complura id genus*, Bacon, *Novum organum*, 338, translated on 339.

[92] The theory is outlined in the first chapter of book one of the 1586 edition; see Telesio, *De rerum natura*, vol. 1, 30-226, at 30-9; for 'faculties', read "facultates", 36, my translation. For Telesio's theory of light, see de Franco, 'La teoria della luce', and Mulsow, *Frühneuzeitliche Selbsterhaltung*, 103-39.

[93] For the dating of the work's composition, see Graham Rees's introduction to *The Oxford Francis Bacon 6*, xxviii-xxxi. Rees suggests that Bacon had access to the 1586 edition of the *De rerum natura* when preparing the work; see his commentary, 425-6, 429 and 430.

present in the *De rerum natura*[94]. Certainly, Bacon devotes a number of pages to describing the association of heat, light, tenuity and motion, and goes on to attack it, with a similar degree of thoroughness, in four points[95]. He acknowledges that such meticulousness may seem over the top, but justifies himself with a comment that has regularly been taken out of context by Telesio specialists: “For I think well of *Telesio*, and recognize him as a lover of truth, a man useful to the science, a corrector of certain doctrines, and the first of the new philosophers”[96].

In any case, Bacon continues, Telesio is significant less in his own right and more as a representative of misguided opinions in this area: “my main reason for going into this so fully is that in dealing with the one that comes first, I speak of many things which can be carried over to the refutation of sects further down the list (which I shall have to deal with presently), and so I shall not have to say the same things time and again”. He concludes forcefully: “For the tendrils of errors (though different) are interconnected and intertwined in strange ways, yet are such that on many occasions they can be mowed and cut down by one refutation, as by a scythe”[97]. The image of mowing down the tendrils of errors in a single, scythe-like refutation is, it goes almost without saying, a powerful one. Bacon’s comment here suggests an obvious motivation for the

[94] Graham Rees also draws this conclusion in his introduction to *The Oxford Francis Bacon 6*, xxix.
[95] Bacon, *De principiis atque originibus*, 224-50.
[96] *De* Telesio *autem bene sentimus, atque eum ut amantem veritatis, & Scientiis utilem, & nonnullorum Placitorum emendatorem & novorum hominum primum agnoscimus*, Bacon, *De principiis atque originibus*, 258, translated on 259. For uses of the comment, see Leijenhorst, ‘Bernadino Telesio’, 170; Mulsow, *Frühneuzeitliche Selbsterhaltung*, 15; and Schuhmann, ‘Le Concept de l’espace’, 143. It also appears in the title of Assenza, ‘Bernardino Telesio: Il migliore dei moderni’.
[97] *Sed illud in primis in causa est, quod hæc fusius agamus, quod in eo, qui primus nobis occurrit, complura disserimus, quæ ad sequentium Sectarum (de quibus postmodum tractandum erit) redargutionem transferri possint, ne sæpius eadem dicere sit necesse. Sunt enim errorum (licet diversorum) fibræ miris modis inter se implicatæ & intextæ, quæ tamen sæpenumero una redargutione, tamquam falce, demeti & succidi possint*, Bacon, *De principiis atque originibus*, 258, translated on 259.

deployment of the method in the *Topica inquisitionis*: he may well have been moved by the desire to prove another philosopher wrong.

In a discussion of what he refers to as Bacon's "relationship of confrontation", Jean-Marie Pousseur has described the extent to which the table of presence in the *Novum organum* is shaped by an engagement with the work of Bernardino Telesio: "The Baconian series must be received for what it is from the start, a *polemical series* directly taking the opposite view to the theses of *De rerum natura*"[98]. He continues with a description of the exclusive operation that precedes the first vintage in the same work: "the instances of the table of presence, propped up by some of those of the table of absence, are used by Bacon as *Instances of Divorce*"[99].

On the one hand, the investigation in the *Topica inquisitionis* extends the polemic that Pousseur identifies in the *Novum organum*: it attacks the Telesian association from another angle, with the items that functioned in the earlier work as instances of divorce between heat and light reappearing, this time as instances of divorce between light and heat. On the other hand, the investigation into light focuses the polemic. Pousseur acknowledges that Aristotelians as well as Telesians viewed heat as a primary principle of the natural world[100]; Bacon's investigation, therefore, has implications outside of his engagement with Telesio. The same is not true when it comes to light. Most obviously, the tables of presence, absence in proximity and degrees in the *Topica inquisitionis* act as a single-minded debunking of the association of light with heat, tenuity and motion. Moreover, the particular focus on the difference between light and heat could well result

[98] Pousseur, 'Bacon, a Critic', 111; the phrase 'relationship of confrontation' appears on 106.
[99] *Ibid.*, 112.
[100] *Ibid.*, 110.

from a recognition that, in Telesio's cosmology, heat corresponds to what Bacon would call the 'form' of light.

In fact, the single-mindedly polemical use of the method in the *Topica inquisitionis* may offer an explanation for the lack of provisional conclusions about the form of light. In the *Novum organum*, the desire to prove Telesio wrong is only one impulse shaping the text and Bacon seems to have attributed some value to a first vintage concerning the form of heat. In the more targeted inquiry in the *Topica inquisitionis*, however, a first vintage would have been redundant. The tables of presence and absence in proximity do the job that he set out to do: they make it abundantly clear that the form of light cannot be, as the Telesian theory would suggest, heat.

Bacon seems to have had little trouble identifying instances of divorce between light and heat, albeit without necessarily using the term. Following the call to arms in the *De augmentis scientiarum*, he mentions some things that are light but not hot: "For see what an immense difference of body there is (if they be considered according to their dignity) between the sun and rotten wood, or even the putrified scales of fish"[101]. And he continues with things that are hot but not light: "Iron, metal, stones, glass, wood, oil, tallow, when they are subjected to fire, either break into flame, or at least become red; but water and air do not acquire any light from the most intense and raging heat, nor cast forth any brightness"[102]. Perhaps the deployment of the method can best be thought of as a means of systematising instances such as these. It can hardly be a coincidence

[101] *Etenim quam immensa est corporis differentia (si ex dignitate considerentur) inter solum et lignum putridum, aut squamas etiam piscium putridas*, Bacon, *De augmentis scientiarum*, 612, translated in vol. 4, 403-4.

[102] *Ferrum, metalla, lapides, vitrum, ligna, oleum, sevum, ab igne, vel flammam vibrant vel saltem rubescunt; at aqua, aër, acerrimo et tanquam furenti calore fervefacta, nihil tamen Lucis adipiscuntur, nec splendent*, Bacon, *De augmentis scientiarum*, 612, translated in vol. 4, 404.

that "flame, wood, metals and other fiery bodies" appear in the table of presence of the *Topica inquisitionis*, alongside "some kinds of rotten wood", while the table of absence in proximity includes the observations: "Boiling water does not give off light" and "air, though violently heated, does not give off light"[103]. The use of the method, then, can be regarded as a polemical tool in a debate: it facilitates the accumulation and arrangement of material, in such a way as to shape disparate observations into a devastatingly persuasive argument.

The idea that Baconian induction involves identifying examples of difference will come as little surprise; indeed, among modern philosophers it is commonly referred to as induction by 'elimination'[104]. The use of the method in the *Topica inquisitionis*, however, suggests that, for Bacon, it was never simply an abstract process, one that aimed in a general way at the advancement of human knowledge. Here, he seems to have been working with a specific difference – that between light and heat – in mind. The deployment of the method in this case, moreover, acts not simply as a means of investigating an aspect of the world, but as a polemical tool in a debate, one that supports his thoughts about light and serves to counter those of another philosopher.

[103] *Flamma, ligna, metalla & alia ignita*; *ligna nonnulla putria*; *Aqua bulliens non edit lucem: aër licit violenter fervefactus non edit lucem,* Bacon, *Topica inquisitionis*, 244 and 246, translated on 245 and 247.
[104] This description was pioneered by John Stuart Mill; see *A System of Logic*, 392. For Bacon's place in the modern history of induction, see Cohen, *An Introduction to the Philosophy of Induction and Probability*, 4-13.

“[L]ook and see whether they give off any light”: Instruments and Experiments

The tables in the *Topica inquisitionis* and *Novum organum* show Bacon’s method at work: they are populated with examples of things that are, or are not, luminous or hot. Many of these examples seem simply to be derived from close observation of the world, but some clearly depend on the experience of manipulating instruments and conducting experiments. Knowledge gained from such practical sources, as will become clear, is most obviously valuable for Bacon as a result of his recognition of the limitations of sense perception; he was keen both to expand and to improve the information available to the investigator. A close focus on his inquiry into light, however, suggests that his use of practical work, like his use of the method, was never simply an abstract process, one aiming at the general advancement of human knowledge about the world. Perhaps unsurprisingly, the findings that he reports tend to support a particular conclusion: that light is distinct from heat.

In the *Novum organum*, Bacon introduces the need for tables in the investigation into heat with a reference to the otherwise capacious and disordered character of his subject-matter: “we must fashion *Tables*, and *Structured Sets of Instances*, marshalled in such a way that the intellect can get to work on them”, he writes, because “*Natural* and *Experimental History* is so various and scattered that it may bewilder and distract the intellect unless it be set down and presented in suitable order”[105]. He never produced a natural history of heat (or of light, for that matter), but the gist of the comment is clear:

[105] Historia *verò* Naturalis & Experimentalis *tam varia est & sparsa, vt Intellectum confundat & disgreget, nisi sistatur & compareat ordine idoneo. Itaque formandæ sunt* Tabulæ, & Coordinationes Instantiarum, *tali modo & instructione, vt in eas agere possit Intellectus*, Bacon, *Novum organum*, 214, translated on 215.

the purpose of the method is to structure natural historical information of the kind that he assigns to part three of the Great Instauration.

In the discussion of natural history in the *Distributio operis*, Bacon provides an insight into his conception of this information: "for those who propose not to divine and guess but to discover and know, and make it their purpose not to fabricate apish mockeries of worlds but to examine and, in a way, dissect the nature of the real world itself, everything should be sought from the things themselves"[106]. A similar comment appears in the *Parasceve, ad historiam naturalem, et experimentalem*; he writes: "we must see above all that it [natural history] has a wide range and is made to the measure of the universe. For the world is not to be tailored to the slenderness of the intellect (which is what has been done hitherto) but the intellect should be stretched and opened up to take in the image of the world as we really find it"[107].

The apparently straightforward, even naive, emphasis in these comments on "the things themselves" and "the world as we really find it" proved predictably difficult to sustain in practice. In the table of presence in the *Topica inquisitionis*, for example, Bacon includes the idea that "the air may hold a soft light adapted to the eyes of animals with night vision"[108]. A note in his discussion of "*Summonsing Instances*", one of the

[106] *Verùm ijs, quibus non conijcere & hariolari, sed inuenire & scire propositum est, quique non simiolas & fabulas Mundorum comminisci, sed huius ipsius veri Mundi naturam introspicere, & velut dissecare in animo habent, omnia à Rebus ipsis petenda sunt*, Bacon, *Distributio operis*, 36, translated on 37.
[107] *antè omnia videndum est, vt latè pateat, & facta sit ad Mensuram Vniuersi. Neque enim arctandus est Mundus ad angustias Intellectûs (quod adhùc factum est) sed expandendus Intellectus, & laxandus, ad Mundi Imaginem recipiendam, qualis inuenitur*, Bacon, *Parasceve*, 458, translated on 459.
[108] *Aër fortasse ipse tenuem possit habere lucem, animalium visui, quæ noctu cernunt*, Bacon, *Topica inquisitionis*, 244, translated on 245.

instances with special powers in the *Novum organum*[109], reveals that this is not an observation derived from his personal experience of the world:

> For *Telesius* has rightly observed that a certain original light exists in the air, though faint and inconsiderable, and which for the most part does not register on human eyes or those of many other animals; because the animals to whose sense light of this kind is suited see in the dark; and that they do this either by an internal light or by no light at all is scarcely credible[110]

In this passage Telesio appears not in the guise that I outlined in the previous section: here, he is not a rival philosopher to be proved wrong, but an authority for an item of knowledge. To highlight the use of a written authority is, however, to be a little unfair to Bacon. The vast majority of the natural historical information contained in the *Topica inquisitionis* seems to have been gained not, in fact, from his reading, but from his experience of things 'as they really are'. The table of presence, for example, features such quotidian examples as "flame", "stars" and "a great mass of snow"[111]. The idea that such things emit light may, of course, have originated in Bacon's books, but, if so, it could easily have been confirmed by everyday sense perception.

There is, however, an obvious problem with any attempt to rely on everyday sense perception. Although the seemingly naive comments that I quoted above may suggest otherwise, Bacon, like many of his contemporaries, was fully conscious of the extent

[109] Instantias Citantes, Bacon, *Novum organum*, 346-58, at 346, translated on 347.
[110] *Rectè enim notauit* Telesius, *etiam in Aëre ipso inesse Lucem quandam originalem, licèt exilem & tenuem, & maximâ ex parte oculis hominum aut plurimorum animalium non inseruientem; quia illa Animalia, ad quorum Sensum huiusmodi lux est proportionata, cernant noctu; id quod vel sine luce fieri, vel per lucem internam, minùs credibile est*, Bacon, *Novum organum*, 358, translated on 359.
[111] *Flamma*; *stellæ*; *magna vis nivis*, Bacon, *Topica inquisitionis*, 244, translated on 245.

to which the experience of the senses can prove faulty[112]. As part of the discussion of the method in the *Distributio operis*, he observes: "Now the sense fails us in two ways: for it either deserts or deceives us". He goes on to provide some examples: "For first there are many things which escape the sense even when it is properly managed and not obstructed at all, because of the subtlety of the body as a whole, or the minuteness of its parts, or its distance from us, or its swiftness or slowness, or the object's familiarity, or other causes besides. And even when the sense does get a grip on something, its hold is not terribly secure"[113]. The expression of the issue here is twofold: the senses are both inadequate and unreliable. Not only do they let us down; they also deceive us. A similar statement appears in book one of the *Novum organum*, as part of a discussion of the "*Idols of the Tribe*", the first of Bacon's four famous 'Idols of the Mind'[114]. Here, he writes that "by far the greatest hindrance and distortion of the human intellect stems from the dullness, inadequacy and unreliability of the senses, so that things which strike the senses outweigh those which, even if they are more important, do not strike them immediately"[115]. Again, the problem has two facets: the senses are both insufficient and untrustworthy.

[112] An emphasis on the faultiness of the senses is a major tenet of sceptical thought; for an overview, see Popkin, *The History of Scepticism*. For Bacon's relationship with contemporary sceptical currents, see Granada, 'Bacon and Scepticism'.
[113] *Duplex autem est Sensûs culpa: aut enim destituit nos, aut decepit. Nam primò, plurimæ sunt res quæ sensum etiam rectè dispositum, nec vllo modo impeditum effugiunt; aut subtilitate totius corporis, aut partium minutijs, aut loci distantiâ, aut tarditate atque etiam velocitate motus, aut familiaritate obiecti, aut alias ob causas. Neque rursùs, vbi Sensus rem tenet, prehensiones eius admodùm firmæ sunt*, Bacon, *Distributio operis*, 32, translated on 33.
[114] For the discussion of "*Idola Tribûs*", see Bacon, *Novum organum*, 82-8. They are introduced on 78-80; the term is on 78, translated on 79. For the discussion of all four "Idola", see 78-112. For an overview, see Rees's introduction to *The Oxford Francis Bacon 11*, li-lvii.
[115] *longè maximum impedimentum & aberratio Intellectûs humani prouenit à stupore & incompetentiâ & fallacijs Sensuum; vt ea quæ Sensum feriant, illis quæ Sensum immediatè non feriunt, licèt potioribus præponderent*, Bacon, *Novum organum*, 86, translated on 87.

In the *Distributio operis*, he outlines his solution: “Now to remedy these defects I have with unswerving devotion to duty everywhere sought and gathered in helps for the sense, in order to make good what is lacking and put right what deceives. And I do this not so much with instruments as by experiments”[116]. He continues: “In fact I set little store by the immediate and peculiar perception of the sense, but carry the matter to the point where the sense judges only the experiment whereas the experiment judges the thing”[117]. The discussion about the idols of the tribe in the *Novum organum* features the same remedy, described in almost identical terms: “For the sense is by nature a weak and wandering thing; and instruments to amplify and sharpen the senses do not count for much; but all true interpretation of nature is accomplished by means of instances, and apt and appropriate experiments, where the sense judges only the experiment while the experiment judges nature and the thing itself”[118].

The idea that experiments can combat the inadequacy of the senses is relatively straightforward: they expand the range of perception, producing new knowledge to stand alongside that gained from everyday experience[119]. The idea that they can combat sensory deceptiveness, on the other hand, is not so obvious and not much clarified by the repeated suggestion that the senses can judge an experiment while the experiment judges nature. For someone who apparently reflected a great deal on the interaction

[116] *Itaque vt his occurratur; nos multo & fido ministerio auxilia Sensui vndique conquisiuimus, & contraximus: vt destitutionibus substitutiones, variationibus rectificationes suppeditentur. Neque id molimur tam Instrumentis, quàm experimentis*, Bacon, *Distributio operis*, 32, translated on 33.
[117] *Itaque perceptioni Sensûs immediate ac propriæ non multùm tribuimus: sed eò rem deducimus, vt Sensus tantùm de Experimento, Experimentum de Re iudicet*, Bacon, *Distributio operis*, 34, translated on 35.
[118] *Sensus enim per se res infirma est, & aberrans; neque organa ad amplificandos Sensus aut acuendos multùm valent; sed omnis verior interpretatio Naturæ conficitur per instantias, & experimenta idonea & apposita; vbi Sensus de experimento tantùm, experimentum de Naturâ, & re ipsa iudicat*, Bacon, *Novum organum*, 86, translated on 87.
[119] For a study of Bacon’s experiments that highlights this role, see Deleule, ‘*Experientia-Experimentum*’. The essay targets, 59-61, the critique of Baconian empiricism contained in Feyerabend, ‘Classical Empiricism’.

between the mind and the world, Bacon leaves his thoughts on this point somewhat underdeveloped. Yet, when it comes to the investigation into light in the *Topica inquisitionis* there is clearly a polemical, as well as an epistemological context to the practical work that is described. It is worth asking whether Bacon's conviction about the value of experimentation may have owed something to the dramatic evidence that it could offer for his ideas about nature.

I will come to his experiments on light shortly, but first it seems worth highlighting that, in both of the passages quoted above, Bacon also mentions instruments. This is, admittedly, in order to dissociate them from experiments, but their very place in these comments seems to testify to the extent to which they are an obvious means of generating new sensory information. Certainly, some of the instances populating the tables in the *Novum organum* and *Topica inquisitionis* betray a degree of familiarity with specialist instrumentation. The table of presence in the earlier work, for example, features: "The Sun's rays reflected and crowded together, as between mountains or by walls, and most of all in burning glasses"[120]. Similar glasses also appear in the *Topica inquisitionis*, as part of a discussion about the "*Multiplications of light*"[121]: "Take note", Bacon writes, "of the multiplication of light, as by perspective glasses and the like with which the light can be brought to a point and projected into the distance or rendered more subtle and better for making out visible bodies – as we see with painters who position a flask full of water in front of a candle"[122].

[120] *Radij Solis reflexi & constipati, vt inter montes, aut per parietes, & maximè omnium in speculis comburentibus*, Bacon, *Novum organum*, 216, translated on 217.
[121] Multiplicationes Lucis, Bacon, *Topica inquisitionis*, 248-50, at 248, translated on 249.
[122] *Videndum de multiplicatione Lucis ut per specula perspectiva & similia, quibus acui potest lux & in longinquum projici aut etiam reddi, ad distinguendas res visibiles subtilius & melius, ut videre est apud pictores, qui phialam aqua plenam ad candelam adhibent*, Bacon, *Topica inquisitionis,* 248, translated on 249.

These references to burning and perspective glasses contain an obvious echo of the descriptions of optical technology that appear in Giambattista della Porta's *Magia naturalis*, first published in 1558 and long recognised as a major source for Bacon's *Sylva sylvarum*[123]. As Graham Rees highlights in his commentary on the *Topica inquisitionis*, however, Bacon was also familiar with more recently invented optical instruments, the microscope and telescope[124]. Indeed, his knowledge of these instruments is clear from a section in the *Novum organum* devoted to one of the instances with special powers, "*Instances of Access* or *Gateway Instances*"[125]:

> Of the first kind [...] are those recently invented glasses which let us see the latent and invisible minutiae of bodies, and their hidden schematisms and motions, by greatly increasing the size of the species. With these glasses we can make out, not without astonishment, the exact shapes and lineaments in a flea, fly or worm, as well as colours and motions not seen before [...] Of the second kind are those other glasses which Galileo's unforgettable enterprise gave us, by the aid of which, as by boats or little ships, we can open up and do better trade with the heavenly bodies[126]

[123] For della Porta's optical instruments, see Borelli, 'Thinking with optical objects'. For the importance of the *Magia naturalis* as a source for Bacon, see Rusu, 'From Natural History to Natural Magic', 141-3.
[124] Rees, 'Commentary', in *The Oxford Francis Bacon 13*, 335. He also highlights Bacon's familiarity with telescopes and microscopes in his introduction to *The Oxford Francis Bacon 11*, xl.
[125] Instantias Ianuæ *sive* Portæ, Bacon, *Novum organum*, 342, translated on 343.
[126] *Primi generis sunt* [...] *ea, quæ nuper inuenta sunt Perspicilla; quæ latentes & inuisibiles Corporum minutias, & occultos schematismos, & motus (auctâ insignitèr specierum magnitudine) demonstrant: quorum vi, in Pulice, Muscâ, Vermiculis, accurata corporis figura & lineamenta, nec non colores & motus priùs non conspicui, non sine admiratione cernuntur* [...] *Secundi generis sunt illa altera Perspicilla, quæ memorabili conatu adinuenit Galilæus: quorum ope, tanquam per scaphas aut nauiculas, aperiri & exerceri possint propiora cum Cœlestibus commercia*, Bacon, *Novum organum*, 342-4, translated on 343.

The microscope and telescope, then, are an obvious source of experiences that fall outside of the realm of everyday sense perception: for Bacon, they let us see minutiae that are otherwise hidden or trade with heavenly bodies that are otherwise closed.

Many of Bacon's references to experimentation in the *Novum organum* and *Topica inquisitionis* most obviously match this conception: like instruments, his experiments seem to aim at the generation of sensory information that would otherwise be unavailable. In the table of absence in proximity in the earlier work, for example, he turns his attention to the instance in the table of presence: "The Sun's rays reflected and crowded together […] most of all in burning-glasses". He proposes: "Do an experiment of this kind. Take a lens made as the reverse of burning-glasses, and place it between the hand and the Sun's rays, and see if it diminishes the Sun's heat in the same way that a burning-glass increases and intensifies it"[127]. The goal of the experiment is clearly new knowledge: the question at issue is whether an alternative design will dissipate heat in the same way as traditional burning glasses focus it.

The desire for new knowledge about heat, however, should not be dissociated from Bacon's interest in the relationship between heat and light. He continues: "For it is obvious as far as optical rays are concerned that the simulacra look bigger or smaller according to whether the glass is thicker in the middle or at the edge. See whether the same is true of heat"[128]. The introduction of observations about the behaviour of light

[127] *Fiat huiusmodi Experimentum. Accipiatur speculum fabricatum, contrà ac fit in speculis Comburentibus, & interponatur inter manum & radios Solis; & fiat obseruatio, vtrùm minuat calorem Solis, quemadmodùm speculum Comburens eundem auget & intendit*, Bacon, *Novum organum*, 222, translated on 223.

[128] *Manifestum est enim quoad radios Opticos, prout fabricatur speculum in densitate inæquali respectu Medij & Laterum, ita apparere simulachra magis diffusa, aut magis contracta. Itaque idem videndum in Calore*, Bacon, *Novum organum*, 222, translated on 223.

in convex and concave lenses suggests that he is concerned with an idea that is familiar from the previous section: the difference between light and heat.

He goes on: "Do a careful experiment to see whether the Moon's rays can be intercepted and concentrated by very powerful burning-glasses of the best quality to even the slightest degree of warmth"[129]. Here, the experiment involves the examination of something that apparently emits light but not heat, the Moon. The following experiment involves things that emit heat but not light: "Let a burning glass also be tried on a heat which is neither radiant nor luminous, like iron or stone heated but not to the point of redness, or like boiling water or similar; and see whether the heat is increased or intensified as it is with the sun's rays"[130]. With all these proposed trials, Bacon is clearly on the hunt for new information, but it appears to be of a particular kind. It can hardly be insignificant that the results of his practical work, if carried out, could serve as instances of divorce between light and heat.

The comments that I have quoted from the *Novum organum* are, of course, proposals for experiments, rather than reports of work that has previously been conducted. Bacon acknowledges the problem, writing after the table of degrees: "Anyone can see how poor we are in history from the *Tables* presented above, where […] I am often reduced to using these phrases: *Perform an Experiment* or *Investigate further*"[131]. The *Topica inquisitionis* ends with a similar recognition of the insufficiency of the instances

[129] *Fiat Experimentum diligentèr, vtrùm per Specula Comburentia fortissima & optimè fabricata, radij Lunæ possint excipi & colligi in aliquem vel minimum gradum teporis*, Bacon, *Novum organum*, 222, translated on 223.
[130] *Practicetur etiam Vitrum Comburens super Calidum, quod non sit radiosum aut luminosum; vt Ferri, & Lapidis calefacti, sed non igniti; aut Aquæ feruentis, aut similium: & notetur; vtrùm fiat augmentum & intentio Calidi, vt in radijs Solis*, Bacon, *Novum organum*, 224, translated on 225.
[131] *Qvàm inopes simus historiæ, quiuis facilè aduertet, cùm in* Tabulis *superioribus* […] *sæpenumerò etiam hisce verbis,* Fiat Experimentum *vel* Inquiratur vlteriús, *vti cogamur*, Bacon, *Novum organum*, 252, translated on 253.

provided: “Now my intention is always that not only are other instances to be investigated […] but also that new topics of inquiry should be added, according as nature brings them up”[132]. The use of the gerundive and the passive voice appears to pass responsibility for further investigation onto the reader, but Bacon seems in fact to have returned to the work and conducted some experiments on light himself.

One item in the table of presence in the *Topica inquisitionis,* which also appears in the table of absence in proximity in the *Novum organum* is “certain kinds of rotten wood”[133]. Bacon subsequently devoted considerable time to investigating this source of luminosity: in the *Sylva sylvarum* he describes the brightness and colour of the light that can be observed; he compares the effects of using different kinds of wood; and he notes the impact of drying a branch, putting it out in frosty weather, boring holes in it and covering it in oil or water[134]. A particularly compelling example of his experimental practice draws on another observation in the *Topica inquisitionis*: “iron and tin when put in aqua fortis to be dissolved boil up and, without any fire, get very hot”[135]. A similar description of the experiment appears in the table of presence in the *Novum organum*[136]; in the later work, however, he continues: “look and see whether they give off any light”[137]. The manuscript collection of notes currently in the British Library shows him following up the suggestion and dissolving iron in nitric acid, this time in the dark: “Take Aqua Fortis; dissolue Iron in it; It boyleth in the dissoluing and casteth

[132] *Intelligo autem semper, quod non tantum aliæ instantiæ inuestigandæ sint* […] *sed etiam, ut novi Topica articuli, prout rerum natura fert, adjiciantur*, Bacon, *Topica inquisitionis*, 256, translated on 257.
[133] *ligna nonnulla putria*, Bacon, *Topica inquisitionis*, 244, translated on 245. “Lignum putre” appears in Bacon, *Novum organum*, 226.
[134] Bacon, *Sylva sylvarum*, 456-7.
[135] *ferrum & stannum, cum in aquam fortem immittuntur resolvenda, ebulliunt & sine igne ullo acrem calorem concipiunt*, Bacon, *Topica inquisitionis*, 244, translated on 245.
[136] Bacon, *Novum organum*, 218.
[137] *utrum vero lucem aliquam edant, inquiratur*, Bacon, *Topica inquisitionis*, 244, translated on 245.

a great Heate; so as you are not able to touch the Glasse: but being tried in the Darke, it giues no light at all; As some Salt Waters by percussion doe"[138].

These experiments, like those proposed in the *Novum organum*, most obviously act to expand the realm of the senses: they generate new knowledge that can stand alongside that gained from everyday sensory experience. Yet, as with the earlier proposals, it is unlikely to be a coincidence that the new knowledge can serve to make a particular point: it demonstrates that light is distinct from the things that Telesio sought to associate with it. The introduction to the investigation into rotten wood in the *Sylva sylvarum* is unusual, in the sense that it suggests that the subject-matter is valuable for its capacity to demonstrate the difference between light and motion[139]. The experiment described in the British Library manuscript, by contrast, involving the dissolution of iron in acid in the dark, acts as a demonstration of what is by now an overwhelmingly familiar idea: light and heat are different.

On the one hand, Bacon's experiments further the progress of the logical method: by extending the reach of sense perception, they increase the quantity of information that is available to the investigator. In highlighting the distinct nature of light, however, they also act to some extent independently. If the deployment of the method in the *Topica inquisitionis* has the principal goal of demonstrating that light is different to heat, the experiments that I have highlighted act as a kind of short cut: they make the same polemical point, but more quickly and dramatically.

[138] Rees, 'An Unpublished Manuscript', 395. The original features deletions and marginal and intralinear insertions that I have not represented here.
[139] Bacon, *Sylva sylvarum*, 456.

The conception of experimentation as a kind of short cut prompts thoughts of Bacon's description of the instances with special powers in book two of the *Novum organum*; at the end of the work, he writes: "the end of my logic is to teach and to instruct the intellect not to batten on and embrace abstract things with the mind's fragile tendrils (as common logic does), but really to slice into nature, and discover the virtues and acts of bodies, and their laws as they are determined in matter, in such a way that this science may emerge not just from the nature of the mind but from the very nature of things". As a result, he continues, "it is no wonder that my text is everywhere shot through and illustrated with reflections and experiments on the nature of things by way of exemplifying my art"[140]. This passage establishes a complementary relationship between the logical method as a whole and the reflections and experiments that are contained within it: the latter could perhaps be viewed as particularly compelling examples of the process of 'slicing into nature'.

This description of the instances with special powers, meanwhile, prompts thoughts of a chapter in the *De augmentis scientiarum*, in which Bacon provides a more abstract discussion of his conception of practical work[141]. Here, he begins by differentiating two uses of the term 'inventio': the first refers to new discoveries made in the arts and sciences; the second to the arrangement of information in contemporary works of logic[142]. He continues: "The former of these I report altogether deficient, which seems to me to be such a deficience, as if in the making of an inventory touching the estate of

[140] *cùm Logica nostra, doceat Intellectum & erudiat ad hoc, vt non tenuibus Mentis quasi Clauiculis rerum Abstracta captet & prenset (vt Logica vulgaris) sed Naturam reuerâ persecet, & Corporum virtutes & Actus, eorumque Leges in Materiâ determinatas inueniat; ita vt non solùm ex Naturâ Mentis, sed ex Natura Rerum quoque hæc Scientia emanet; Mirum non est, si vbique Naturalibus Contemplationibus & Experimentis, ad Exempla Artis nostræ, conspersa fuerit & illustrata*, Bacon, *Novum organum*, 442, translated on 443.
[141] Bacon, *De augmentis scientiarum*, 617-33.
[142] *Ibid.*, 617. For a discussion of this distinction, see Jardine, *Discovery and the Art of Discourse*, 69-70.

a deceased person, it should be set down that ‘there is no ready money’”[143]. He then distinguishes two ways of making discoveries – the first by means of his new method; the second by what he calls ‘learned’ or ‘literate experience’[144] – before observing: “though the rational method of inquiry by the Organon promises far greater things in the end, yet this sagacity proceeding by Learned Experience will in the meantime present mankind with a number of discoveries which lie near at hand, and scatter them like the donations that used to be thrown among the people”[145].

It may also help to think of Bacon’s practical work with regard to his description of part five of the Great Instauration, the “*Precursors*, or *Anticipations of the Philosophy to Come*”[146]. No surviving works can be confidently assigned to this section, but in the *Distributio operis* he describes it as “a temporary measure pending completion of the rest, rather like interest payable until the principal can be had”[147]. Speaking metaphorically, then, the ‘anticipations of the philosophy to come’ provide cash in hand, discoveries that tide the philosopher over until the work of the Great Instauration is done. Perhaps one thing, to pursue the analogy, that this ready money could be spent on is the demonstration that another philosopher’s ideas are wrong.

[143] *Priorem harum* desiderari *prorsus pronuncio. Qui quidem talis mihi videtur esse defectus, ac si quis in inventario conficiendo bonorum alicujus defuncti ita referat,* Numeratæ pecuniæ nihil, Bacon, *De augmentis scientiarum*, 617, translated in vol. 4, 407-8.

[144] Bacon, *De augmentis scientiarum*, 622-4.

[145] *Quamvis enim Via Rationalis per Organum longe majora spondeat, attamen hæc Sagicitas per Experientiam Literatam plurima interim ex iis quæ in proximo sunt in genus humanum (tanquam missilia apud antiquos donativa) projiciet et sparget*, Bacon, *De augmentis scientiarum*, 628, translated in vol. 4, 417. James Spedding uses the term ‘invention’ in his translations, where I prefer ‘discovery’.

[146] *Prodromi*, siue *Anticipationes Philosophiæ Secundæ*, Bacon, *Distributio operis*, 26, translated on 27.

[147] *At quinta pars ad tempus tantùm, donec reliqua perficiantur, adhibetur; & tanquàm fœnus redditur, vsque dum sors haberi possit*, Bacon, *Distributio operis*, 42, translated on 43.

In her article '*Experientia literata* or *Novum organum*?', Lisa Jardine diagnoses Bacon as a case of "scientific split personality", a thinker who adopted "two conflicting strategies for dealing with the single problem of scepticism concerning access to knowledge of natural phenomena". She continues: "To observe that Bacon unfortunately tried to take both escape routes simultaneously is at once to diagnose his philosophical failure, and to explain the rich and fruitful ambiguity of his historical influence"[148]. To Jardine's judgement could perhaps be added a note about his polemical success. Certainly, when it comes to his work on light, the deployment of practical work combines with the deployment of the method to create an overwhelmingly powerful argument, one directed at Bernardino Telesio's association of light with heat, tenuity and motion. Bacon's experiments on light, together with his use of the method, make a compelling case: in no way can the form of light be heat.

***

As will be seen in my discussion of Robert Hooke's work in chapter three, Francis Bacon's practical activity in the field of optics provides a valuable context for the inquiries conducted by members of the early Royal Society. His exemplary instances of things that emit light but not heat – glow-worms, rotten wood *etc.* – served as regular touchstones for Hooke and other Society Fellows' interest in luminescence. Meanwhile, his belief in the potential of the telescope and microscope proved well-founded, with Hooke's drawings of the microscopic world acting as a powerful testimony of the achievements of the new science. Finally, his work provided a reference point for the construction of a natural philosophy that was founded on

[148] Jardine, '*Experientia literata* or *Novum organum*?', 60-1.

experimentation, acting not simply as an authority to be invoked, but – if Robert Boyle's efforts to focus the light of the Moon, reported in his book on the nature of cold, are anything to go by – as an inspiration for specific experimental investigations.

Of course, Bacon was not working with this audience in mind. In fact, it is worth noting that the principal expression of his disagreement with Telesio's thought on light seems to have been a private piece of writing: the *Topica inquisitionis* was not published until 1658 and there is no evidence that it circulated in manuscript. Likewise, the experiment involving the dissolution of iron in acid in the dark was never deployed in a public forum: unlike many of the comments in the collection of notes that is now lodged in the British Library, there is no analogous passage in the *Sylva sylvarum*. If the context of Bacon's work on light was polemical, then, the target may have been personal. Rather than convince a reader, he seems to have been looking to bolster his own suspicions about the difference between light and heat. His target audience was clearly not a broad one; it may even have been limited to himself.

Thomas Hobbes Fires a Gun into a Lake

It seems safe to say that Thomas Hobbes (1588-1679) is a thinker best known for his works of moral and political philosophy. He has, however, received broader study than some of his celebrated contemporaries: in the introduction to *The Cambridge Companion to Hobbes*, for example, Tom Sorrell stresses that his writings "range far beyond morals and politics". Indeed, they "go beyond philosophy in the narrow modern sense altogether, to include full-scale treatises in physics, optics and geometry"[1]. The book, accordingly, includes chapters on Hobbes's method of natural science, on his mathematics and on the relationship between his scientific and his political writings[2]. In a contribution detailing his work on light and vision, Jan Prins writes: "Like many of his contemporaries, Hobbes showed a keen interest in optics". "In fact", he continues, "his search for an explanation of vision led him to believe that all natural phenomena could be reduced to local motion of material bodies". For Prins, then, optics is of fundamental importance within Hobbes's work, as the arena in which he developed his approach to natural philosophy: "from the very start, his theory of light and vision served as a model for his theories of natural phenomena in general"[3].

For his contribution to the *Cambridge Companion*, Jan Prins was able to draw on his own work situating Hobbes's writings in the tradition of geometrical optics, as well as on Alan Shapiro's study of what he has termed 'kinematic optics'[4]. The years since

---

[1] Sorrell, 'Introduction', 1.
[2] Jesseph, 'Hobbes and the Method of Natural Science', Grant, 'Hobbes and Mathematics', and Sommerville, 'Lofty Science and Local Politics'.
[3] Prins, 'Hobbes on Light and Vision', 129.
[4] Prins, 'Kepler, Hobbes and Medieval Optics', and Shapiro, 'Kinematic Optics', 143-72. See also Bernhardt, 'Hobbes et le mouvement de la lumière' and 'L'œuvre de Hobbes', Blay, 'Genèse des couleurs et modèles mécaniques', and Stroud, 'Light and Vision'.

have seen further publications, including books by Franco Giudice and Frank Horstmann[5]. The number of studies now available may suggest that Hobbes's optics has been exhaustively covered, but there is, in fact, something missing from all these works: there has, thus far, been no substantial discussion of his interest in, and use of, optical instruments and experiments. Unlike Baconians, Hobbes scholars are familiar with their subject's optics. They are, however, less familiar with his practical optics.

This chapter, then, seeks to provide an overview of Hobbes's practical work in optics. The first section sets his writings of the 1630s and 1640s in the context of his membership of an intellectual network, one that also included William Cavendish, Earl of Newcastle, his brother Sir Charles Cavendish, and their chaplain Robert Payne. The second highlights his considerable interest in a range of optical instruments, which I view as playing a role in the development of his mechanistic natural philosophy. Finally, the third describes some of his experiments on light, which I regard as stemming at times from curiosity and at other times from a desire to prove a rival philosopher wrong. This chapter has to devote more energy to establishing the practical credentials of its subject than is the case for those on Francis Bacon, Robert Hooke and Isaac Newton. Nevertheless, the second theme of the thesis – the value of practical work in a polemical context – remains present: as will be seen, a *leitmotif* running through the following discussions is Hobbes's consistently confrontational relationship with his great contemporary René Descartes.

[5] Giudice, *Luce e visione*, and Horstmann, *Nachträge zu Betrachtungen*. See also Giudice, 'Optics in Hobbes's Natural Philosophy', Malet, 'The Power of Images', and Medina, 'Hobbes's Geometrical Optics'.

“[B]red out of priuate talke”: Hobbes’s Philosophical Career

In 1630, Hobbes’s philosophical career was in its infancy. The term ‘philosophical career’ is, of course, anachronistic[6], but it encapsulates an idea that early modern thinkers would, I suspect, have recognized: that life as a philosopher comprises both the production of philosophical work and the cultivation of philosophical contacts[7]. On both counts, Hobbes’s career before 1630 was undeveloped. As biographers have highlighted, he had hardly been inactive, but no philosophical work dating from before this point can indisputably be ascribed to him and the evidence for significant philosophical connections is slender[8]. The 1630s did not necessarily witness the dawn of his philosophical interests, but, as will be seen, these years certainly mark the start of his philosophical career. As the period features his first statements on optics, an interest that reached its height in the work of the following decade, it seems appropriate to ask: what was the catalyst for the change?

Between 1628 and 1630, Hobbes was on the continent in the company of the son of a Nottinghamshire landowner, Sir Gervase Clifton; when he returned to England he took up a post as tutor to William Cavendish, the third Earl of Devonshire[9]. He had

[6] Noel Malcolm makes this point in ‘A Summary Biography of Hobbes’, 13.
[7] The significance of networks in early modern intellectual activity has been emphasised by recent scholarly projects such as ‘Cultures of Knowledge’, for details of which see www.culturesofknowledge.org. See also Lux and Cook, ‘Closed Circles or Open Networks?’ and Pumfrey and Dawbarn, ‘Science and Patronage’.
[8] For an overview of Hobbes’s activities pre-1630, see Malcolm, ‘Hobbes, Thomas’ and ‘A Summary Biography’, 13-21. Noel Reynolds and Arlene Saxonhouse have suggested that Hobbes is the author of three of the essays in *Horæ subseciuæ*, a collection published anonymously in 1620. They make the ascription based on wordprint studies; see Reynolds and Saxonhouse, ‘Hobbes and the *Horæ subsecivæ*’. In his life of Hobbes, John Aubrey suggests that he worked as a secretary for Francis Bacon; see *Brief Lives*, vol. 1, 322-403, at 331. There is some contemporary evidence for a connection between the two men, but there is little for one of any significance; for a full discussion, which to my mind makes more of the evidence than it warrants, see Bunce, ‘Hobbes’s Relationship with Bacon’. Aubrey’s life of Hobbes is not included in Kate Bennett’s new edition of *Brief Lives*.
[9] For Hobbes’s letters to Sir Gervase Clifton from the continent and following his return, see Letters 4, 5 and 8, in Malcolm, ed., *The Correspondence of Thomas Hobbes*, vol. 1, 10-2, 13-5 and 17. See also

previously served with the Devonshires as the tutor to the second Earl, also called William, and it seems likely that he would have had at least some contact in these years with the second Earl's cousins, William Cavendish, the Earl of Newcastle, and his brother, Sir Charles, whose properties at Welbeck Abbey and Bolsover Castle lie within a day's travel of the Devonshire residences of Hardwick Hall and Chatsworth House[10]. Significant interactions, however, can only be dated to the first half of the 1630s: Noel Malcolm's edition of Hobbes's correspondence suggests that, by the middle of the decade, he had become part of an intellectual network that included the two brothers and Robert Payne, William's chaplain and secretary from 1630[11].

In total, there are nine surviving letters from between 1634 and 1641, seven from Hobbes to William, one from Hobbes to Charles and one from Payne to Hobbes, with references to others now lost[12]. Suggestively, all the surviving correspondence was written when Hobbes was away from home, in London in 1634, on a tour of the continent with the third Earl of Devonshire between 1634 and 1636, during a stay at the house of Thomas Bruce in Byfleet in Surrey in 1636 and following his return to France in 1640. Equally suggestive is the fact that no correspondence survives from his previous time on the continent. We have limited evidence, then, but what we have points to the existence of an intellectual network forged in person during the years

---

'Sir Gervase Clifton' and 'William Cavendish, third Earl of Devonshire', in Malcolm, 'Biographical Register', 820-3 and 815-7.

[10] For an overview of Hobbes's relationship with the second Earl of Devonshire, see Lee, 'Cavendish, William'. For his relationship with the Newcastle Cavendishes, see 'William Cavendish, first Earl, first Marquis and first Duke of Newcastle' and 'Sir Charles Cavendish', in Malcolm, 'Biographical Register', 812-5 and 801-5.

[11] For Robert Payne's place in the network, see Malcolm, *Aspects of Hobbes*, 80-145, at 88-96. Payne's employment is dated to 1630 on 88.

[12] Letters 10, 16, 18, 19, 21, 22, 23, 24 and 31 in Malcolm, ed., *The Correspondence of Thomas Hobbes*, vol. 1, 19-20, 28-30, 32-3, 33-6, 37-8, 39, 40-1, 41-2 and 80-6. References to other letters appear in Letters 18, 22, 23 and 31, at 32, 39, 40 and 80.

1630-4, after Hobbes's return to the employment of the Cavendishes and the arrival of Robert Payne, and sustained during periods of separation in 1634-6 and after 1640.

A 'Cavendish circle', sometimes referred to as a 'Welbeck' or 'Newcastle' circle, has been the focus of some study by literary and intellectual historians, although with little agreement about whom exactly the network comprises[13]. Descriptions of the circle, again with little consensus on its membership, also commonly feature in biographies and general studies of Hobbes[14]. I have, however, not found a work that limits the network to these figures and to this time period, nor one that seeks to establish its role in the development of Hobbes's philosophical career.

There is no direct evidence for Hobbes's relationship with members of the group during the early years of the 1630s, but his subsequent correspondence betrays a considerable degree of familiarity. In a letter to the Earl of Newcastle of October 1636, for example, sent from Byfleet in Surrey, he invites himself to Welbeck so that he can pursue his studies: "I must not deny myself the content to study in y[e] way I haue begun", he writes, "& that I cannot conceaue I shall do any where so well as at Welbecke, and therefore I

[13] Raylor, 'Newcastle's Ghosts', and Jacquot, 'Sir Charles Cavendish and his Learned Friends'. See also the special issue of *The Seventeenth Century* dedicated to the circle, vol. 9, no. 2 (1994). Raylor includes Walter Warner and Ben Jonson; Jacquot includes Warner, Pierre Gassendi and Marin Mersenne. The special issue of *The Seventeenth Century* has two articles on Ben Jonson and two on John Westwood. It also features a re-examination of the atomism of the circle, which includes discussions of the work of Walter Warner, Pierre Gassendi, Walter Charleton, Sir Kenelm Digby and Margaret Cavendish; see Clucas, 'The Atomism of the Cavendish Circle'. This article is a response to Kargon, *Atomism in England*, 63-76.
[14] See Bernhardt, *Hobbes*, 17, Martinich, *Hobbes*, 98-102, Pacchi, *Introduzione a Hobbes*, 16, Reik, *The Golden Lands*, 66-8, and Rogow, *Thomas Hobbes*, 108-11. Bernhardt and Martinich include Walter Warner; Pacchi includes Warner, John Pell and Sir Kenelm Digby; Reik includes Ben Jonson, John Dryden and William Davenant; Rogow includes Warner, Jonson, Dryden, Davenant and Pell. Noel Malcolm has suggested that "[t]he phrase 'Welbeck Academy' is just a metaphor for a group of people connected with the Cavendish brothers and does not refer to physical gatherings either formal or informal"; see 'A Summary Biography of Hobbes', 23. This view is echoed in Bunce, *Thomas Hobbes*, 6-7.

meane if yo^{r} Lo^{p} forbid me not, to come thither as soone as I can, and stay as long as I can without inconuenience to yo^{r} Lo^{p}"[15].

It is tempting to think that Welbeck was attractive for Hobbes because it offered the space and time necessary to produce philosophical work, but, in a letter sent shortly afterwards, he suggests that contact with William is also a factor: "The hope of not being long from yo^{r} Lo^{p}, makes me let Philosophy alone till then; and then if I haue any thinge you shall fetch it out, by discourse for by that meanes I shall take in as much more, and so be no looser"[16]. In an earlier letter, sent to William from Paris in August 1635, Hobbes suggests that discourse is also characteristic of his relationship with Robert Payne; indeed, he explicitly equates his relationships with the two men, despite the obvious differences in wealth and status: "let me tell yo^{r} Lo^{p} once for all, that though I honor you as my Lord, yet my Loue to you is iust of y^{e} same nature that it is to m^{r} Payne, bred out of priuate talke, without respect to yo^{r} purse"[17].

In the dedication of his translation of Thucydides' account of the Peloponnesian War, published in 1629, Hobbes wrote to the third Earl of Devonshire, stressing his sense of obligation to the Earl's late father; he feels "bound in duty to bring it in as an account to him, by whose indulgence I had both the time and ammunition to perform it"[18]. By contrast, he dedicated *The Elements of Law*, a manuscript work dated 1640, to William, Earl of Newcastle, making clear the relationship between it and previous discussions with his patron: "Now (my Lord) the principles fit for such a foundation, are those

[15] Letter 21, in Malcolm, ed., *The Correspondence of Thomas Hobbes*, vol. 1, 37.
[16] Letter 22, in Malcolm, ed., *The Correspondence of Thomas Hobbes*, vol. 1, 39.
[17] Letter 16, in Malcolm, ed., *The Correspondence of Thomas Hobbes*, vol. 1, 28.
[18] Hobbes, *The History of the Grecian War*, vol. 8, iii-vi, at iii.

which I have heretofore acquainted your Lordship withal in private discourse, and which by your command I have here put into method"[19].

It is, of course, possible that these descriptions of productive private discourse had no basis in reality, but it seems plausible to ascribe to the Cavendish circle a supportive intellectual atmosphere that Hobbes, perhaps feeling the impact of the contemporary vogue for Italianate courtesy literature, conceptualised in terms of conversation[20]. His relationship with the Cavendishes, then, certainly provided space and time, but it also provided a nurturing philosophical environment.

Hobbes's place in the Cavendish circle also appears to have facilitated contact with figures outside of the network. In a letter sent to Robert Payne sent in October 1634, for example, the mathematician and natural philosopher Walter Warner expressed his appreciation of Hobbes's previous communication with him[21]. Two years later, Payne suggested that, while Hobbes was at Byfleet in Surrey, he might take the opportunity to visit Warner at nearby Cranbourne Lodge, the residence of the latter's patron Sir Thomas Aylesbury[22]. It is difficult to know whether Hobbes profited from the proximity – in a message to William written on Christmas Day he explained that he had not yet visited, because floods had made the roads impassable[23] – but his membership of the Cavendish network certainly led to other intellectual encounters. In the same letter of October 1634, Warner writes, as part of a discussion on refraction: "I would

[19] Hobbes, *The Elements of Law*, xv-xvi, at xvi.
[20] For the impact of such literature in early modern England, see Richards, *Rhetoric and Courtliness*, 1-19. For the importance of conversation, see Bryson, *From Courtesy to Civility*, 153-6.
[21] Walter Warner to Robert Payne, in Halliwell, ed., *A Collection of Letters*, 65. For an overview of Warner's life and career, see Clucas, 'Warner, Walter'.
[22] Letter 23, in Malcom, ed., *The Correspondence of Thomas Hobbes*, vol. 1, 40. For Aylesbury's patronage of Warner, see Alsbury, 'Aylesbury, Sir Thomas'.
[23] Letter 24, in Malcolm, ed., *The Correspondence of Thomas Hobbes*, vol. 1, 41.

be very glad to see Mons^r^. Mydorge's way; yf he make a secret of it, I doubt not but Mr. Hobbes will know how to trafik with him"[24]. Hobbes subsequently vindicated this faith in his ability to handle the French mathematician Claude Mydorge: in a letter of June 1636, sent to William from Paris, he reports: "Mydorgius tels me he has sent to S^r^ Charles his treatise of refraction perfected"[25].

While in Paris in the middle part of the decade, Hobbes also seems to have encountered the French intellectual hub Marin Mersenne and the diplomat and natural philosopher Sir Kenelm Digby[26]. In 1637, after Hobbes's return to England, the latter sent him a copy of René Descartes's newly printed *Discours de la méthode*, a work that clearly made a profound and lasting impression[27]. In 1640, Hobbes began an exchange of letters with Descartes, sent via Mersenne, which continued after his arrival back in Paris that year[28]. At one point, in a letter sent in March 1641, the aristocratic members of the Cavendish circle make a sudden appearance in the correspondence: fearing that Descartes may one day agree with his theory of "the nature and production of light, sound, and all phantasms or ideas" and claim "that it was founded on his own principles", Hobbes insists that he first elaborated it back in 1630 in front of "those

[24] Warner to Payne, in Halliwell, ed., *A Collection of Letters*, 65.
[25] Letter 18, in Malcolm, ed., *The Correspondence of Thomas Hobbes*, vol. 1, 32. For Mydorge's correspondence with Sir Charles Cavendish, see 'Sir Charles Cavendish', in Malcolm, 'Biographical Register', 802.
[26] In a letter to Mersenne of 30 March 1641, Hobbes refers to a discussion having taken place seven years previously; see Letter 34, in Malcolm, ed., *The Correspondence of Thomas Hobbes*, vol. 1, 102-7, at 102. For an overview of the relationship, see 'Marin Mersenne', in Malcolm, 'Biographical Register', 862-5. For evidence of Hobbes's relationship with Digby, see Letters 20, 25, 26 and 27, in Malcolm, ed., *The Correspondence of Thomas Hobbes*, vol. 1, 36-7, 42-9, 50-1 and 51. See also 'Sir Kenelm Digby', in Malcolm, 'Biographical Register', 828-32.
[27] The letter accompanying the *Discours de la méthode* is Letter 27, in Malcolm, ed., *The Correspondence of Thomas Hobbes*, vol. 1, 51. For discussions of the impact of Descartes's work on Hobbes, see Bernhardt, 'La polémique de Hobbes', Brandt, *Hobbes's Mechanical Conception*, 129-42, Marquer, 'Ce que sa polémique', Tuck, 'Hobbes and Descartes', and Zarka, 'La matière et la représentation'.
[28] Letters 29, 30, 32, 33, 34 and 36, in Malcolm, ed., *The Correspondence of Thomas Hobbes*, vol. 1, 54-6, 62-70, 86-9, 94-7, 102-7 and 116-7, translated on 57-60, 70-9, 89-92, 97-100, 107-13 and 118-9.

most excellent brothers William Earl of Newcastle and Sir Charles Cavendish", describing the latter as his and Mersenne's "mutual friend"[29].

To some extent, the circle, minus Robert Payne, reformed in 1645, when, after a period of continental wandering, William and Sir Charles arrived in Paris[30]. According to the memoirs of William's second wife, Margaret Cavendish, Hobbes came to dinner[31]; meanwhile, Sir Charles makes a number of references to him in letters to the mathematician John Pell, suggesting on one occasion, in a postscript: "If we remoue from hence directing your packet to M^{r}: Hobbes he will conuei it to me"[32].

By this point, however, Hobbes's philosophical career was flourishing. In 1641, he had contributed the third set of 'objectiones' to Descartes's *Meditationes de prima philosophia*, published alongside Descartes's responses[33]. At some point between December 1640 and April 1642, he was at work on what is known as the 'Latin Optical Manuscript'[34]. His first published piece of political philosophy, *De cive*, appeared in November 1642[35]. In his editorial introduction to the work, Howard Warrender suggests that it was financed by Sir Kenelm Digby and circulated by Marin Mersenne[36]. During the years 1642-3 he prepared a lengthy manuscript critique of Thomas White's

[29] *me doctrinam illa de naturâ et productione luminis, et soni, et omnium Phantasmatum siue idearum* [...] *explicasse Coram Dominis fratribus excellentissimis Gulielmo Comite de Newcastell* [et] *Carolo* [*Cauendisiti* altered to *Cauendish* by Hobbes] *Equite aurato communi nostro amico, anno 1630*, Letter 34, in Malcolm, ed., *The Correspondence of Thomas Hobbes*, pp. 102-3, translated on 108.
[30] For an overview of the Cavendishes' time on the continent and in Paris, see Carlyle, 'Cavendish, William'. Payne remained in England; see Feingold, 'Payne, Robert'.
[31] Cavendish, *Philosophical and Physical Opinions*, B3^{v}. For an overview of Hobbes's relationship with Margaret Cavendish, see Malcolm, 'Biographical Register', 811-2.
[32] Letter 40, in Malcolm, ed., 'The Pell-Cavendish Correspondence', 429-30, at 429. For other references to Hobbes, see Letters 34, 52, 72, 412-3, 461-2, 502-4, at 412-3, 461, 502. For an overview of the relationship between Pell and Cavendish, see Malcolm, 'The Life of John Pell', 85-93.
[33] Hobbes, 'Objectiones ad meditationes'.
[34] Hobbes, 'Latin Optical Manuscript'. For this dating, see Raylor, 'The Date and Script', and Malcolm, 'Hobbes, the Latin Optical Manuscript'.
[35] Hobbes, *De cive*.
[36] Warrender, 'Introduction', 6-7.

De mundo dialogi tres, which was annotated by Mersenne[37]. Then, in 1644, the latter printed a number of his pieces on natural philosophy, including one on optics[38].

During this period, probably via Mersenne, Hobbes seems to have encountered the mathematician Thomas de Martel, who sent Samuel Sorbière a copy of *De cive*[39], as well as the celebrated philosopher Pierre Gassendi, who supported its republication in 1647[40]. In a letter of July 1645, Sorbière wrote to Hobbes from Lyon, describing a request that appears to confirm that, by this point, his place among the philosophers of his era had been established: "I have asked de Martel to send me portraits of you, the great Gassendi, and the excellent Mersenne". He continues: "For I am moved and impelled to be virtuous not only by writings but also by the faces of great men; I feel, as it were, an emanation, a natural force which radiates from them to me"[41].

The partial reformation of the Cavendish circle in the mid-1640s, then, had no obvious impact on a philosophical career that, by this point, was already thriving. But it did have one result that is significant for this chapter: Hobbes spent late 1645 and early 1646 working on a treatise on optics in English, *A Minute or First Draught of the Optiques*,

[37] Hobbes, 'Anti-White'. For a description of Mersenne's marginal comments, see Jean Jacquot and Harold Whitmore Jones's introduction, 92-3. I follow Noel Malcolm in referring to this untitled piece as 'Anti-White'; see Malcolm, 'The Title of Hobbes's Refutation'.
[38] The pieces were published in in *Cogita physico mathematica* and *Universæ geometriæ*; for Hobbes's contributions, see Schuhmann, 'Hobbes dans les publications', and Malcolm, 'General Introduction', in *Thomas Hobbes: Leviathan*, 3n. The work on optics is *Tractatus opticus*.
[39] See 'Thomas de Martel' in Malcolm, 'Biographical Register', 848-55, at 850. For an overview of Hobbes's relationship with Sorbière, see 893-9.
[40] See 'Pierre Gassendi' in Malcolm, 'Biographical Register', 834-6, at 835.
[41] *rogaui Martellum vt Iconem tuam, magni Gassendi, optimíque Mersenni mihi impetraret quam summopere jam efflagito, ratus aequi boníque te consulturum expeditionis meae libertatem. Non solùm enim scripta me mouent & ad virtutem impellunt, afficit quoque me vultus virorum maximorum, a quibus in me veluti effluuium, diffusámque vim insitam sentio*, Letter 38, in Malcolm, ed., *The Correspondence of Thomas Hobbes*, 121-2, translated on 122-3; the quote is from 122, translated on 123.

which is by far the longest exposition of his thoughts in the field[42]. Like the earlier *Elements of Law*, the work is dedicated to William, Earl of Newcastle and, in terms that recall his previous descriptions of a conversational relationship, Hobbes writes in the preface of his hope that “it will sufficiently giue your Lo^{pp} satisfaction, in those quares you were pleased to make concerning this subject”[43].

The making of Hobbes’s philosophical career cannot, of course, be attributed solely to his membership of the Cavendish circle. I have no desire to underestimate the extent to which he was willing and able to capitalise on opportunities as they arose. It is, however, the existence of those opportunities that is the focus of this section: his relationship with the Cavendishes, I am suggesting, provided him not only with the space, time and supportive atmosphere necessary to produce philosophical work, but also with the connections necessary to make it as a philosopher.

[42] Hobbes, *A Minute or First Draught*. The work is dated 1646, but is mentioned in a letter from Sir Charles to John Pell, written on 11 November 1645; see Letter 42 in Malcolm, ed., ‘The Pell-Cavendish Correspondence’, 433-5, at 434. A critical edition is available in Elaine Stroud’s unpublished PhD dissertation, ‘Thomas Hobbes’s *A Minute or First Draught of the Optiques*’, 79-639. I will be quoting from the original, which has been digitised by the British Library and is, therefore, the more easily available source. Where appropriate, I will refer to Stroud’s commentary.

[43] Hobbes, *A Minute or First Draught*, 2^r-4^r, at 3^v.

“I haue enquired concerning perspectiues”: Optical Instruments

In the contribution to the *Cambridge Companion* that I referenced in the introduction to this chapter, Jan Prins describes Hobbes’s work in optics as the attempt to translate “the scholastic explanations of light and vision” into “mechanical terms”. In this sense, he writes: “his theory of light and vision served as a model for his theories of natural phenomena in general”[44]. The broader process that he is alluding to here is neatly summarised in the title of Cees Leijenhorst’s *The Mechanisation of Aristotelianism*. Within Leijenhorst’s book, however, the second term gets much more attention than the first: he seeks to situate Hobbes’s mechanism – his belief that all natural phenomena can be understood as the local motion of material bodies – within the context of late Aristotelian natural philosophy. Quite rightly, he emphasises that Hobbes and other ‘moderns’ were part of “an intellectual setting steeped in Aristotelianism”. And he insists: “However much they may have striven to cast aside two thousand years of Aristotelianism, they were obviously forced to formulate their alternatives in terms comprehensible to those standing within that tradition”[45].

Leijenhorst, then, focuses more on the Aristotelian context for Hobbes’s mechanistic philosophy than on the process that is implicit in the word ‘mechanisation’: he does not ask himself how a philosopher steeped in an Aristotelian intellectual setting could arrive at a mechanical conception of the universe. A question along these lines is, however, the starting-point for an essay by Helen Hattab on Hobbes’s contemporary, René Descartes. Her answer lies in the “revival” and “boost in status” seen during the

[44] Prins, ‘Hobbes on Light and Vision’, 129. For an overview of Hobbes’s mechanistic philosophy, see Brandt, *Hobbes’s Mechanical Conception*.
[45] Leijenhorst, *The Mechanisation of Aristotelianism*, 7 and 3.

sixteenth century in the ancient art of mechanics, a broad field that covers the workings of a range of mechanical devices: she traces a "historical link between the *mechanica* tradition and Descartes", before highlighting some "conceptual affinities between the explanations found in the *Quæstiones mechanicæ* and Descartes's mechanistic explanations"[46]. Yet, as these comments make clear, her account is one of a philosopher who, on the whole, was more engaged with the mechanical tradition than with any actual mechanical devices. Descartes, in her essay, is principally someone who read about practical work, rather than someone who conducted it[47].

Thomas Hobbes, as will be seen, did both. He clearly paid considerable attention to the descriptions of practical activity contained in Descartes's *Dioptrique*, one of the three essays accompanying the *Discours de la méthode* of 1637[48]. But he also had a deep and personal interest in the workings of a number of optical instruments: the newly invented telescope and microscope, as well as the older burning glass and *camera obscura*[49]. He was an active reader, in the sense that he considered the words on the page in the light of conclusions drawn from his and others' experience. Indeed, I will suggest that both of these features of his optical work – reading and practice – are present in the development of his mechanistic conception of the eye.

Optical devices were a subject of significant interest for members of the Cavendish circle. In the early years of the 1640s, Sir Charles Cavendish engaged John Pell in a

---

[46] Hattab, 'From Mechanics to Mechanism', 99 and 103. For a survey of sixteenth-century mechanics, see Rose and Drake, 'The Pseudo-Aristotelian *Questions of Mechanics*'. For ancient mechanics, see Berryman, *The Mechanical Hypothesis*.
[47] Jessica Riskin's consideration of Descartes's mechanism in the context of his actual experience of mechanical devices was published after the completion of this section; see *The Restless Clock*, 44-71.
[48] Descartes, *La Dioptrique*.
[49] For overviews of these instruments, see Mills, 'Burning Glasses', and Hammond, *The Camera Obscura*.

project to construct a telescope with lenses shaped into hyperbolic curves, a design proposed by Descartes in the ninth discourse of *La Dioptrique* as a means of producing distinct images[50]. Hobbes was certainly aware of the project, possibly before its inception; in a letter of February 1641, he writes to Sir Charles from Paris: “I haue enquired concerning perspectiues after y[e] manner of de Cartes, Mydorgius tells me there is none that goes about them, as a thing too hard to do. And I beleeue it, For here is one mons[r] de Bosne in towne, that dwells at Bloys, an excellent workeman [...] he telles me he hath tryed De Cartes his way but cannot do it”[51].

The gentle scepticism expressed in this letter appears to have been justified. Little progress in Sir Charles’s project is evident before the autumn, apparently due to the difficulties involved in getting hold of glass of good enough quality[52]. In November he assumed that one of the lenses would shortly be completed and provided detailed instructions for testing it[53]. But, in a letter sent in early January 1642, Pell reports: “I was to bee last Friday (Dec. 14) at M[r] Reeves house there I found the glasse broken, he told me y[t] as soone as the diamond touched it y[e] Cement let it goe because of y[e] weather and y[e] polished smoothnesse of y[e] flat side of y[e] glasse: it served him so 3 times & in putting it on the 4th time y[e] fire brake y[e] glasse”[54]. Sir Charles’s response is remarkably sanguine – he writes simply: “I hope fine glass differs so little in refraction that it will

[50] See Malcolm, ‘The Life of John Pell’, 91-2. The ninth discourse is Descartes, *La Dioptrique*, 196-211; for the description of the design with hyperbolic lenses, see 201-5. For a study of Descartes’s design and attempts to realise it, see Burnett, *Descartes and the Hyperbolic Quest*.
[51] Letter 31, in Malcolm, ed., *The Correspondence of Thomas Hobbes*, vol. 1, 85. Noel Malcolm describes Florimund de Beaune as a lawyer, mathematician, lens-grinder and astronomer; see 86n.
[52] For references to difficulties obtaining glass, see Letters 1 and 2, in Malcolm, ed., ‘The Pell-Cavendish Correspondence’, 335-6 and 337-8, at 335 and 337. For the challenges involved in getting hold of glass in this period, see Bedini, ‘Lens Making’, 687-8.
[53] Letter 5, in Malcolm, ed., ‘The Pell-Cavendish Correspondence’, 343.
[54] Letter 9, in Malcolm, ed., ‘The Pell-Cavendish Correspondence’, 349-350, at 349. For the sake of clarity, I have removed Malcolm’s indications of intralinear insertions. For an overview of the life and career of the optical instrument maker Richard Reeve, see Simpson, ‘Reeve, Richard’.

not doe vs much harme"[55] – but it is difficult to imagine that this tale of breakages did not provoke at least some frustration. As Noel Malcolm observes in his editorial notes, a comment in Pell's papers reveals that a completed convex lens was delivered in early February[56]. By this point, however, the project seems to have been abandoned, with slow progress a possible contributing factor.

Sir Charles's experience of the Cartesian design appears to have had a considerable impact on Hobbes. In a letter, sent from Paris in November 1645, Sir Charles informs Pell, now based in Amsterdam, that Hobbes disapproves of a new book by the astronomer and instrument-maker Anton Maria Schyrleus von Rheita, "because he commends hyperbolick glasses, aboue sphaericall, for perspectiues"[57]. A chapter devoted to telescopes and microscopes in the *Minute or First Draught of the Optiques*, written at about the same time, features a lengthy critique of the use of hyperbolic lenses, based on the fact that they focus light to a point, whereas, Hobbes claims, a better design would allow for further focusing to happen within the eye[58]. After explaining his preference for spheres, he writes: "I think it necessary to shew that y^e same effect is nott to bee had from 2 glasses hyperbolicall", continuing:

> which to shew would nott haue beene so necessarie, if it had nott bene, that y^e Opinion hath beene so taken upon authoritie of others, as it hath nott onely hindred diuers men from speculation of y^e Optiques as a thing already perfected

[55] Letter 10, in Malcolm, ed., 'The Pell-Cavendish Correspondence', 351.
[56] See Malcolm, ed., 'The Pell-Cavendish Correspondence', 349n.
[57] Letter 43, in Malcolm, ed., 'The Pell-Cavendish Correspondence', 436. Malcolm references the book, 436n., as *Oculus Enoch et Eliæ*.
[58] The chapter is Hobbes, *A Minute or First Draught*, 173^r-192^r; the critique is 180^v-184^r.

> butt hath also caused diuers lovers of this science to bestow much labor and cost in vaine for the cutting of hyperbolicall glasses[59]

The alleged hindering of speculation in optics prompts thoughts of Thomas White's suggestion that telescopes have reached their perfect form, which is lamented in Hobbes's manuscript discussion of the *De mundo*[60]. In light of their tribulations, meanwhile, it is difficult not to think of the "diuers lovers of this science", who have bestowed so much labour and cost in vain, as a reference to Sir Charles and John Pell. The allusion to the "authoritie of others", of course, needs little glossing.

Despite his experience, Sir Charles's enthusiasm, both for telescopes and for Descartes's design, seems to have been undimmed; in a letter sent to Pell in August 1644 from Hamburg, he describes the telescopes of the instrument-maker William Gascoigne: "I onlie mislike his glass next to the eye which he makes conuex on both sides, I tolde him it woulde make confused sight, if De Cartes his doctrin be true"[61]. In January of the following year, he hears that Anton Maria Schyrleus von Rheita has moved to Antwerp and asks his correspondent to look into buying a telescope on his behalf[62]. In a later letter to Pell, sent in February 1648, he includes this instrument in a lengthy description of his and his brother's collection:

> it seems that Polander hath a verie good perspectiue glass but I hope not so goode as Fontanus glass; for wee haue that heer; presented to my brother from

[59] *Ibid.*, 180^{v}.
[60] Hobbes, 'Anti-White', 175.
[61] Letter 17, in Malcolm, ed., 'The Pell-Cavendish Correspondence', 369-70, at 369. For the life and career of William Gascoigne, see Chapman, 'Gascoigne, William'.
[62] Letter 30, in Malcolm, ed., 'The Pell-Cavendish Correspondence', 401-2, at 401.

> S^r Kenelm Digbie [...] I thinke I writ to you of 3 glasses my brother hath of Eustacio Divinios whom some esteem a better worckman than Fontanus [...] my brother hath allso 2 of the famous Tauricello but wee haue not yet tried them./ he hath allso another of 37 palmes at least as I take it, made by Eustacio Diuino, which if it be well wrought, will douteless excell all the rest[63]

He continues: “he hath yet an other to come from P: Reita, which I heare is ariued in the Lowecountries & hath bin there as I remember they writ tried & saied to be verie rare”. And he concludes, with a certain degree of understatement: “So that wee are & shall be prettie well furnished with perspectiues”[64].

As Noel Malcom observes in his editorial notes, with the exception of von Rheita’s, these telescopes were sold to Hobbes when the Cavendishes left Paris later in 1648. Of course, it seems safe to assume that he would have had access to the collection before this point. From the absence of von Rheita’s instrument, Malcolm suggests: “it may be deduced either that it never arrived, or that it was judged superior to all the others and retained by Newcastle”[65]. Given Hobbes’s disapproval of von Rheita’s preference for hyperbolic lenses, an alternative possibility must be that it arrived, but he did not want it. The question is hardly clear-cut: refusing to buy an item from his patron would be an odd thing to have done. What seems clear, though, is that he had considerable experience of telescopes and distinct ideas about their design.

---

[63] Letter 72, in Malcolm, ed., ‘The Pell-Cavendish Correspondence’, 502-4, at 502-3. For details of the instrument-makers mentioned here, see Noel Malcolm’s footnotes. The quote features an intralinear insertion.
[64] *Ibid.*, 503
[65] Malcolm, ed., ‘The Pell-Cavendish Correspondence’, 503n.

Hobbes writes less about microscopes, but he evidently had a similar level of experience of these devices. Alongside his critique of the Cartesian telescope in the *Minute or First Draught*, he reports the effectiveness of a microscope, “which I haue caused to bee made for my selfe”[66]. In his description of the device, the lenses are, unsurprisingly, spherical[67]. The emphasis here, however, is as much on effective manipulation as it is on design. He provides, for example, some thoughts about the best sizes for lenses[68], but these are preceded by a lengthy account of how to focus correctly, which includes, to take just one example, the observation: “a great cause why such glasses are many times nott neate and distinct, as they might bee is the ill polishing, whereby furrowes beeing left, all ouer, the glasse cast a false light ouer the whole object”[69]. Such remarks as this are clearly based on familiarity with the microscope as an instrument that is actually used: Hobbes is certainly interested in questions of design, but he is also acquainted with some of the more quotidian things that can impede successful handling, such as ineffective polishing.

Like his thoughts about telescopes and microscopes, Hobbes’s consideration of burning glasses owes something to his membership of the Cavendish circle. In 1635, the mathematician Walter Warner sent Sir Charles Cavendish two tracts, one about the place of an object viewed in a mirror, the other, now lost, apparently involving designs for optical instruments[70]. Hobbes expressed notably pragmatic doubts about the latter in a letter to William, Earl of Newcastle, sent in the August of that year: “I vnderstand not how m^{r} Warner will demonstrate those inuentions of the multiplying glasse and

[66] Hobbes, *A Minute or First Draught*, 191^{r}.
[67] *Ibid.*, 191^{r}-191^{v}.
[68] *Ibid.*, 190^{v}-191$^{v.}$
[69] *Ibid.*, 188^{r}-190^{v}, at 189^{r}.
[70] The surviving tract is *De loco imaginis*; see Malcolm, ed., *The Correspondence of Thomas Hobbes*, vol. 1, 35n.

burning glasse so infinite in virtue as he pretends". He continues: "so when it is demonstrated how y^{e} glass must be made to burn a mile of, if the glasse must be so bigge as cannot be made, the art will be no more worth, then the art of making ordinary burning glasses"[71]. The thrust of Hobbes's response, then, is that Warner has overstated his case: it is all very well to provide a design for an improved microscope or burning glass, but the instrument is useless if it cannot be made.

Sir Charles responded to Warner in September 1636, referring him to concerns set out in a letter from Robert Payne[72]. The latter detailed four points, the last of which is: "whether the hand or tool of any artificer be able to worke the formes or moulds, and consequently the superficies of the glasse so true, as that to nature they shall be distinguished from other convexe superficies, as the spheriques, coniques, etc"[73]. The question contains an echo of Hobbes's emphasis on practicability, although where he was concerned about the problems involved in realising the size of the design, Payne appears to have focussed more on the difficulties presented by a complex shape, a point that Sir Charles Cavendish could perhaps have reflected on five years later, when he and John Pell came to construct a Cartesian telescope.

In a chapter of the *Minute or First Draught* devoted to "places of burning", Hobbes compares burning by reflection, by means of a mirror, with burning by refraction, by means of a lens[74]. The only suitable designs for a burning mirror, he suggests, are concave spherical and parabolic curves; he writes: "nor doe I see how with these [...]

[71] Letter 16, in Malcolm, ed., *The Correspondence of Thomas Hobbes*, vol. 1, 28-9.
[72] Sir Charles Cavendish to Walter Warner, in Halliwell, ed., *A Collection of Letters*, 67.
[73] Robert Payne to Walter Warner, in Halliwell, ed., *A Collection of Letters*, 67-9, at 69.
[74] The chapter is Hobbes, *A Minute or First Draught*, 54^{v}-65^{r}.

one can possibly burne anything at any greate distance, by reflection"[75]. This is not, however, the case when it comes to burning with lenses, which "may bee caused at any distance assigned, & with more and more vehemence"[76]. At the root of this interest in burning at a distance is probably the legend that Archimedes employed burning glasses to destroy the Roman fleet during the siege of Syracuse, which was widely reported in the period, not least in the discussion of lenses in *La Dioptrique*[77]. It is, however, tempting to think that Hobbes may still have been mulling over Walter Warner's claim about a glass that could burn at the distance of a mile.

In his discussion of burning with lenses, Hobbes goes on to weigh up the advantages of hyperbolic over elliptic curves, before concluding: "Butt all things considered, I am of opinion a sphæricall glasse is of most use, for though it draw nott all y^e paralell beames to a point precisely yett it doth sufficiently to burne". He continues: "and because all sphæres are like, all sphæricall glasses will produce the effect, butt for an hyperbolicall or an elliptique glasse, whereas those figures are of infinite varieties, there is onely one kind that serues y^e turns [...] and y^e hyperbole or ellipsis must bee formed thereunto, which is very difficult & subject to error"[78]. In these comments, Hobbes's preference for spheres is articulated solely in pragmatic terms. In the case of telescopes and microscopes, discussed above, he insists that the best design involves spherical lenses, because they allow for the focusing that takes place in the eye. Here, he acknowledges that hyperbolic or elliptic curves would result in more effective burning glasses; the only reason he prefers spheres is because they are easier to make. This passage, then,

---

[75] *Ibid.*, 58^v.
[76] *Ibid.*, 61^v.
[77] Descartes, *La Dioptrique*, 165-196, at 194. For other references that Hobbes could have encountered, see Mersenne, *Livre de l'utilité*, C5^r, and Galilei, *Discorsi e dimostrazioni matematiche*, 86.
[78] Hobbes, *A Minute or First Draught*, 62^v.

does not simply reveal his interest in practical optics; it also emphasises his experience of, and pragmatic attitude to, the subject.

Another optical instrument intriguing members of the Cavendish circle at this time was the *camera obscura*. In a letter of October 1636, Hobbes outlined a theoretical explanation for the image cast in the device, apparently in response to a question from William, Earl of Newcastle: “The lucide body”, he writes, “as for example, the sunne, lighting on an obiect, as for example, the side of a house doth illuminate it [...] This light mingled, or colour, passing through the hole […] giues the paper in the part where it falles a power to diffuse light euery way, and so it comes to y^{e} eye wheresoeuer they stand”[79]. In the *Minute or First Draught,* he devotes a chapter to the instrument, which he opens: “If wee suppose a roome bee so close shutt, as there is no admittance of light, but at one hole, and y^{t} so little as to give entrance to a small imperceptible beame, y^{e} illumination will be imperceptible”. This looks like an unpromising start, but he continues: “butt if it were possible that at y^{e} least hole, y^{e} illumination should bee sufficient whatsoever were illuminate without y^{e} roome, and opposite to y^{e} hole, would be represented most perfectly within the roome upon a paper or white wall”[80].

The comment in the *Minute or First Draught*, compared with that in the letter, is initially somewhat difficult to grasp, but it appears to relate to the results of practical work that is outlined later in the chapter. Hobbes describes experimenting with the *camera obscura*, using holes of different sizes. He concludes that the relationship between the brightness and the clarity of an image is inversely proportional: a larger

[79] Letter 21, in Malcolm, ed., *The Correspondence of Thomas Hobbes*, vol. 1, 37-8.
[80] Hobbes, *A Minute or First Draught*, 32^{r}-34^{v}, at $32^{r\text{-}v}$. The first quote features an intralinear insertion.

hole produces a brighter but less clear image, whereas a smaller hole produces a clearer but less bright one[81]. When it comes to the description of the *camera obscura* at the beginning of the chapter, he seems to have extrapolated that the clearest image would be one where the hole is infinitesimally small; of course, the brightness would also be infinitesimally small, so the image would be imperceptible.

The idea that the hole in a *camera obscura* must let in enough light for the image to be perceptible seems obvious enough, but Hobbes apparently felt compelled to return to it on the following page: "This [the image] would, bee most accurate and mathematically distinct in case y[e] hole were a mathematicall point, Butt because that cannot bee, and because y[e] hole […] must bee of considerable greatnesse, there must also bee confusion in such pictures, as are made through a hole"[82]. There is a curious obsessiveness in his desire to hammer this point home, which is perhaps explicable with reference to the contemporary use of Euclidian geometry as the traditional means of modelling the behaviour of light[83]. Geometrically speaking, it is perfectly possible to represent a beam of light as a straight line (considered as having a length but no width), which can pass through a mathematical point (considered as having no dimensions at all)[84]. Hobbes's emphasis on the fact that the hole must have a physical size seems to have at root a vaguely expressed recognition that geometry is not a particularly profitable way of approaching the *camera obscura*: a hole with no actual dimensions would, of course, not let in any actual light.

[81] *Ibid.*, 32[v]-33[r].
[82] *Ibid.*, 32[v].
[83] For an overview of the geometrical tradition, see Lindberg, *Theories of Vision*, 104-208.
[84] The first two axioms of Euclid's *Elements* are that a point has no physical dimensions and that a line has a length but no width. The two copies of the work included in the bibliography were in Robert Payne's library and are now in the Savile collection in the Bodleian Library in Oxford; see Malcolm, *Aspects of Hobbes*, 144-5, at 145.

It is tempting to view the discussion of the *camera obscura* in this chapter of the *Minute or First Draught* in terms of practice vs. theory: practical experience with an optical instrument seems to have highlighted the deficiencies in the contemporary theoretical model for the behaviour of light. Hobbes was, however, already working with an alternative theory in mind. In a later chapter, dedicated to the projection of images, he makes the same point as before: "how can there bee a hole so little, as a point? nay if it were so little, there would passe no beame at all". This time, he continues: "For by beame is understood y^e way in the aire, or other medium moued in a straite lyne, not a line it selfe, taken mathematically without latitude"[85].

Hobbes's statement here regarding his conception of a beam of light acts as a neat summary of the mechanistic theory that he had developed over previous years: a beam is to be understood not as a geometrical line, but as a movement with a physical width[86]. The first, and best known, expression of his theory appears in a letter to William, Earl of Newcastle, sent in October 1636: "But whereas I vse the phrases, the light passes, or the coulor passes or diffuseth it selfe, my meaning is that the motion is onely in y^e medium, and light and coulor are but the effects of that motion in y^e brayne"[87]. The comment is regularly quoted in studies of Hobbes's theoretical optics[88], but what often passes unmentioned is the context: the outline of the theory follows immediately the description in the same letter, quoted above, of the image produced in a *camera obscura*. No connection is stated between the experience of the instrument and the

[85] Hobbes, *A Minute or First Draught*. The chapter is 46^v-54^v; the quotes are from 47^v. The second has an intralinear insertion.
[86] Jan Prins describes the idea that light has width as well as length as an "essential contribution to a truly mechanically based optics"; see 'Hobbes on Light and Vision', 134. For Hobbes's relationship with the geometrical tradition, see Prins, 'Kepler, Hobbes and Medieval Optics', 298, and Shapiro, 'Kinematic Optics', 160-4.
[87] Letter 21, in Malcolm, ed., *The Correspondence of Thomas Hobbes*, vol. 1, 38.
[88] See Bernhardt, 'Hobbes et le mouvement de la lumière', 6; Giudice, *Luce e visione*, 135; Prins, 'Hobbes on Light and Vision', 132; and Shapiro, 'Kinematic Optics', 165.

theoretical conception of light, but it is difficult not to think that the former played some kind of a role in the formation of the latter.

Additional light can be thrown on the place of instruments in the development of Hobbes's mechanistic worldview, with reference to his mechanistic conception of the eye. The chapter in the *Minute or First Draught* devoted to the casting of images discusses three ways of improving projection: Hobbes refers to the *camera obscura* and to the focussing of light by means of a lens, but he concludes that the best design makes use of both[89]. Even so, perfect projection is only to be found in a single case: "such a figure", he writes, "is not to bee expected from y^{e} Geometry or hand of Man; God onely is y^{e} Architext of such a figure; and y^{t} figure it is, hee hath giuen to y^{e} Eye"[90].

Interestingly, the second half of this comment (from 'God onely') is struck through and replaced with the following: "yet such a property hath the figure of the ey, as farre as concernes the optique axe precisely". The deletion is intriguing, given the accusations of atheism that Hobbes's work prompted: the suggestion that the nature of the eye cannot be explained or replicated by human means is maintained in the corrected version, but it is hard to know what to make of the effacement of God[91]. For my purposes, of course, the significant point is that optical instruments are no longer the subject of interest; the projection of images in the *camera obscura* and the focussing of light in a lens now serve as ways of thinking about the eye.

[89] Hobbes, *A Minute or First Draught*, 47^{v}-48^{r}.
[90] *Ibid*., 50^{v}-51^{r}.
[91] For contemporary accusations of atheism, see Mintz, *The Hunting of Leviathan*, 39-156. Jessica Riskin has highlighted the prevalence of the idea that the eye functions like an instrument in slightly later arguments for divine design; see *The Restless Clock*, 78-87. Hobbes's deletion seems to mark him out as an exception in the trend.

Treating the eye like an instrument, a kind of perfect combination of a *camera obscura* and a lens, is a recognisably mechanistic way of thinking. There is no mention here of the ‘spirits’ that natural philosophical and medical thinkers of a previous generation might have had reference to[92]. Hobbes continues simply: “For such is ye nature of a perfect eye that if there bee opposed to it an object ABC (whether ye Eye remayne in ye head or bee taken out) and you take any part in it as A all ye beames yt fall from it within ye Compasse of ye pupill of ye Eye will bee refracted to ye point a. in ye bottome of ye Eye […] by the diuersity of Refraction which ye diuersity of ye 3 humors in substance and figure maketh”[93]. This description of the organ is clearly informed by an understanding of optical instruments, although Hobbes’s recognition of the difficulty involved in explaining the eye by human means remains apparent: his reference to the “substance” and “figure” of the three humours is notably vague.

It is also worth noting the rather grisly parenthesis, according to which projection occurs whether the eye remains in the head or is taken out. This comment suggests that Hobbes’s conception of the eye may have been based not simply on familiarity with instruments, but also on experience of dissection. The idea seems to be confirmed by what follows: “And though no man can bee so well assured of ye quantity of refraction which ye seuerall humors make”, he writes, “yett experience maketh manifest that ye Image in that point, to one yt shall haue an eye in his hand, and looke on ye hinderpart of it […] shall bee seene as distinctly as ye object itselfe”[94].

[92] For an overview of early seventeenth-century medical conceptions of vision, which were principally Galenic, see Vanagt, ‘Early Modern Medical Thinking’, 573-8. For an overview of Galen’s ‘pneumatic’ theory of vision, see Boudon-Millet, ‘Vision and Vision Disorders’.
[93] Hobbes, *A Minute or First Draught*, 51r.
[94] *Ibid*, 51v.

Taken together, these passages look like compelling evidence for the existence of a practical dimension to Hobbes's optics. He appears as a philosopher whose theoretical conception of vision was fundamentally shaped by his hands-on experience of instruments (and, it turns out, of dissection). These comments are, however, in fact close paraphrases of the opening to the fifth discourse of *La Dioptrique,* which is dedicated to the projection of images in the eye. There, Descartes discusses the structure of the organ with reference to a *camera obscura* and a lens and describes the dissection of the eye of a fresh corpse[95]. Of course, the fact that Hobbes paraphrased *La Dioptrique* is hardly fatal for my vision. He may not have conducted any dissections (although he may have done[96]), but he certainly had the practical knowledge of instruments that was necessary to engage with Descartes's discussion of the eye: the idea that it functions along the lines of a *camera obscura* and lens would have been meaningless to someone without his experience of those devices.

It seems safe, then, to conclude that Hobbes's mechanistic conception of the eye was shaped both by his reading of Descartes's *La Dioptrique* and by his interest in, and practical experience of, optical devices. This conclusion, moreover, prompts the thought that the development of his mechanistic philosophy in general – the mechanisation of his Aristotelianism – may have owed something to his experience with instruments. At the very least, the material presented here suggests that, just as no discussion of his optics is complete without reference to his practical optics, no discussion of his mechanism can afford to ignore his mechanisms.

[95] Descartes, *La Dioptrique*, 114-29, at 114-7. For Johannes Kepler's similarly mechanistic conception of the eye, see Gal and Chen-Morris, 'Empiricism without the Senses'.
[96] John Aubrey suggests that William Petty studied dissection with Hobbes at this time; see *Brief Lives*, vol. 1, 336-7.

“[C]ertayne experience can confute”: Experimental Optics

Thomas Hobbes’s attitude to experiments is probably one of the most famous aspects of his natural philosophy, thanks to his conflict with Robert Boyle in the 1660s about the possibility of a vacuum, a conflict that Steven Shapin and Simon Schaffer have influentially depicted as a clash about the value of experimentation. They mention J.W.N. Watkins’s attempt to refute “the popular idea that Hobbes despised experiments” and maintain: “The point to be made is not that Hobbes ‘despised’ experiment [...] What Hobbes was claiming, however, was that the systematic doing of experiments was not to be equated with philosophy: going on in the way Boyle recommended for experimentalists was not the same thing as philosophical practice. It was not the case that one could ground philosophy in experimentally generated matters of fact”[97]. As they stress, of course, their conclusion is not the same as saying that Hobbes thought that experiments “ought not to be performed” or that they “had no significant place in a properly constituted philosophy of nature”[98].

The focus of Shapin and Schaffer’s study is what they view as Hobbes’s methodological dispute with Robert Boyle and, accordingly, they frame his take on experimentation in negative terms: what he did *not* think experiments capable of. Their book, then, could leave a reader wondering: what value did he ascribe to experiments? Did he accord them a significant place in a properly constituted philosophy of nature? If so, what was it? This sections examines some of Hobbes’s experiments on light and suggests that, at times, he seems to have been moved by a spirit of curiosity, sharing

[97] Shapin and Schaffer, *Leviathan and the Air-Pump*, 181-4. The quotes are from 181 and 184. They reference Watkins, *Hobbes’s System of Ideas*, 46n.
[98] Shapin and Schaffer, *Leviathan and the Air-Pump*, 184.

with many of his contemporaries a sense of wonder at the marvels that could be produced by mechanical means[99]. Elsewhere, however, he seems to have considered experiments valuable for their capacity to invalidate theories about the world: as will be seen, he may not have thought experimentation capable of grounding philosophy, in the sense of providing it with solid foundations, but he did think experiments capable of grounding philosophical ideas, in the sense of bringing them down to earth.

In a letter to William Cavendish, sent in July 1636, Hobbes writes of "thinges that are not demonstrable, of w^{ch} kind is y^{e} greatest part of Naturall Philosophy" that "the most that can be atteyned vnto is to haue such opinions, as no certayne experience can confute, and from w^{ch} can be deduced by lawfull argumentation, no absurdity"[100]. In this formulation, experience can serve a polemical function: it can confute a natural philosophical opinion. This polemical sense of the value of experience plays out later in the same letter, when Hobbes turns to a treatise that Walter Warner has sent to Sir Charles Cavendish on the place of an object viewed in a mirror[101].

He writes to William: "I pray yo^{r} Lo^{p} let him see that peece of y^{e} conuexe glasse wherein appeare the Images of the firre trees, and see if he can applye his reasons to it, and demonstrate why the Images of those trees w^{ch} are long since perhaps burnt a thousand mile hence should be in that place where they are". He continues: "If the experiment of y^{e} mans image in y^{e} glasse of bloud might be made againe, and shewed him I would

[99] For the power of wonder in this period, see Campbell, *Wonder and Science*, Daston and Park, *Wonders and the Order of Nature*, and the essays published in Deckard and Losonczi, eds., *Philosophy Begins in Wonder*. As Alexander Marr notes, 'curiosity' and 'wonder' are overlapping concepts; see his introduction to Evans and Marr, eds., *Curiosity and Wonder from the Renaissance to the Enlightenment*.

[100] Letter 19, in Malcolm, ed., *The Correspondence of Thomas Hobbes*, vol. 1, 33.

[101] The treatise is Warner, *De loco imaginis*. For Hobbes's later work on the place of an image, see Malet, 'The Power of Images'.

haue him answer to that also"[102]. The polemical thrust of these comments seems clear: the experiments that Hobbes refers to do not exactly invalidate Warner's ideas, but they certainly reveal their limitations. Indeed, Hobbes's use of the word 'demonstrate' is significant: just before these calls for experimentation, he praises Warner as one of the ablest men in Europe when it comes to optics, but he criticises him for calling his writings 'demonstrations', because his "grounds and suppositions" regarding light are "vncertayne and many of them not true"[103].

Hobbes tries to provide an explanation for the appearance of the image of the fir trees, noting that it is difficult to do so with the discipline of optics as it currently stands, and he concludes by urging the repetition of the second experiment: "I pray you my Lord if you can conueniently let that experiment of the bloud, eyther of a man or horse be tryed againe. for it deserues to be knowne for y^e^ wonder"[104]. In general, the polemical tenor of Hobbes's appeal to experimentation seems clear. This particular comment, however, suggests another kind of value that he may have ascribed to experiments. The appearance of a human figure in a glass of blood seems to have piqued Hobbes's curiosity. The experiment deserves repeating, he writes, for the wonder.

The most prominent use of the term 'experiment' in the *Minute or First Draught of the Optiques* appears in a chapter on refraction: after a discussion of the refraction of light at oblique angles and in materials of different densities, Hobbes poses two questions. Firstly, to what degree does light refract in any particular piece of glass? Secondly, how much does it refract at different angles? He continues: "For y^e^ first it can bee knowne

[102] Letter 19, in Malcolm, ed., *The Correspondence of Thomas Hobbes*, vol. 1, 34.
[103] *Ibid.*, 34.
[104] Letter 19, in Malcolm, ed., *The Correspondence of Thomas Hobbes*, vol. 1, 34.

only by experiment, but beeing knowne y^{e} Second is known by raciocination". The experiment in question involves covering one side of a triangular prism, leaving only a small hole open to the sun; a beam of light passes through the hole, the refraction of which can be measured (see figure 1)[105]. Hobbes does not mention his source for this set-up, but he clearly owes it to technology described in the tenth discourse of Descartes's *La Dioptrique* (see figure 2)[106].

[105] The chapter is Hobbes, *A Minute or First Draught*, 12^{r}-21^{r}. The quote is from 16^{v} and features the intralinear correction of a spelling mistake.
[106] Descartes, *La Dioptrique*, 211-2. Similar descriptions, this time with references to Descartes, appear in Hobbes, 'Latin Optical Manuscript', 171, and 'Tractatus Opticus', 232.

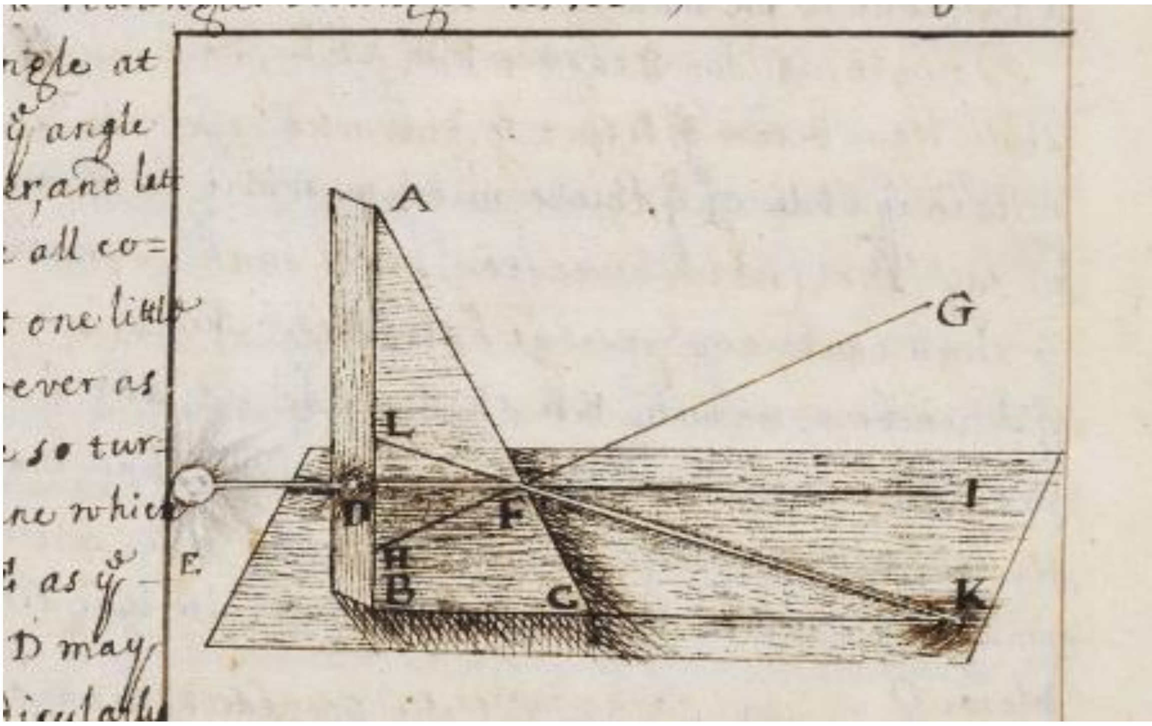
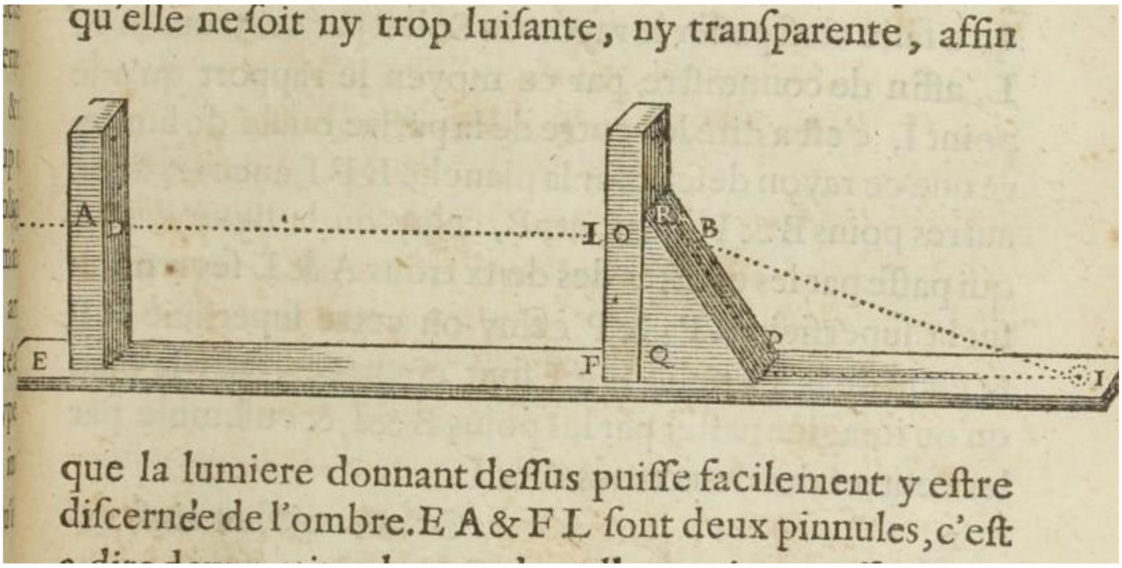


Fig. 1 Hobbes, *A Minute or First Draught of the Optiques*, 16ᵛ, accessed via www.bl.uk/manuscripts.


qu'elle ne ſoit ny trop luiſante, ny tranſparente, affin

que la lumiere donnant deſſus puiſſe facilement y eſtre diſcernée de l'ombre. E A & F L ſont deux pinnules, c'eſt

Fig. 2 Descartes, *La Dioptrique*, in *Discours de la méthode*, S1ʳ, Bibliothèque Nationale de France RESM-R-76 – accessed via www.gallica.bnf.fr.

Being able to measure the refraction of light in a piece of glass was important in this period, because the construction of the material was such an imperfect process. Later in the *Minute or First Draught*, Hobbes provides a vivid account of the extent to which the quality of a lens could depend on vagaries in its manufacture: “it happens many tymes, that a glasse, though smooth and playne both behind and before, shall nevery^{e}lesse so cast y^{e} beames that by Refraction passe through it, as that, that which in y^{e} object is a straight line, shall bee cast crooked”. Such crookedness occurs “not only when y^{e} Refraction is greater in one part of y^{e} Superficies than another, y^{e} parts of y^{e} glasse being of different tempers, but also by the manner of cooling glasse from y^{e} furnace, when in y^{e} cooling it takes such an unequall agitation in y^{e} parts, as to giue the glasse an evident Grayne, which graine usually appeares in y^{e} breaking: and as it makes y^{e} Glasse apter to breake one way than another, so also it makes it both by reflexion and refraction to cast y^{e} beames bias, or one way more than another”[107].

The challenges involved in the manufacturing process are clear, as are the consequences. Given the rudimentary nature of the technology involved, any predictions about the quality of the end product would have been impossible: the only viable option was to make some glass and then test its refraction. As Hobbes observes: “it is but by chance, y^{t} One lights on a very good peece of glasse Especially for a perspectiue of greate length, in which euery little error is multyplied”[108].

Once the refraction of light has been measured at one angle of incidence, the refraction at all other angles can be determined, as Hobbes writes, by ‘ratiocination’. The allusion

[107] Hobbes, *A Minute or First Draught*, 22^{v}-23^{r}.
[108] *Ibid.*, 23^{r}. For lens-making technology of the period see Bedini, ‘Lens Making’, and Ilardi, *Renaissance Vision*, 224-35.

is to what is now known as 'Snell's Law': as long as the density of the glass is consistent, the refraction of light can be calculated mathematically. There is, then, no obvious polemical aspect to this use of practical work: the experiment serves simply as a necessary source of data for the completion of a calculation.

The refraction of light in a triangular prism is, of course, a subject associated with another seventeenth-century English philosopher, Isaac Newton[109]. A later chapter in the *Minute or First Draught* shows Hobbes conducting similar experiments to those subsequently made famous by his compatriot: he describes three ways of arranging a prism, the second of which involves pointing one corner towards the sun. As he observes, the light refracts in such a way as to produce colours: "red, and then yellow […] blew, then violett"[110]. He goes on to provide a series of notes about the various effects that can be produced by experimenting with elements of the set-up, such as the strength of the light and the angle at which it strikes the glass[111]. The inspiration for his activity almost certainly came from observations about the rainbow in Descartes's essay *Les Météores*, published, like *La Dioptrique*, alongside the *Discours de la méthode*[112]. Hobbes's investigation, however, includes comments that bear no resemblance to his source. As part of his trials, for example, he seems to have projected the refracted light onto coloured bits of paper; he reports that the colour of the light can alter the appearance of the paper, "as of blew to make greene and of yellow a stronger yellow as Orange colour, or weaker as straw colour"[113].

109 I discuss aspects of Newton's work in optics in chapter four below.
110 Hobbes, *A Minute or First Draught*, 65^{r}-71^{r}, at 67^{v}-68^{r}.
111 *Ibid.*, 70^{r-v}.
112 Descartes, *Les Météores*. The discourse is 325-44; the observation that colours can be produced in a glass prism is 330-2. For a discussion of Descartes's experimental work on colours, see Buchwald, 'Descartes's Experimental Journey'.
113 Hobbes, *A Minute or First Draught*, 69^{v}.

This experiment may have been prompted by the idea, expressed in an earlier chapter of the work, that the colours of objects are determined by imperceptibly small shapes on their surface; he writes: “if a man describe on a paper such a figure as hath its inæquality of superficies consisting of cones and another of portions of sphæres, placing the lucid body and his Eye how hee will, hee shall perceive in y^e former that no beame shall bee reflected to y^e Eye, and in y^e latter, there shall bee no sphærick atome from which some beame shall nott bee reflected to y^e Eye” (see figure 3)[114]. Projecting coloured light onto coloured paper could perhaps be viewed as a means of investigating a theory of this kind. Certainly, the fact that the light appears darker once it has been reflected from darker-coloured paper supports the idea that some of it has been trapped in the shapes on the paper’s surface, although how light reflected from lighter-coloured paper could appear lighter is not clear.

[114] *Ibid.*, 29^r-32^r, at 30^v. Hobbes attributes the idea to the French Jesuit philosopher Honoré Fabri. Like Elaine Stroud, I have been unable to identify the work in which Fabri expresses it; see ‘Thomas Hobbes’s *A Minute or First Draught*’, 191n.

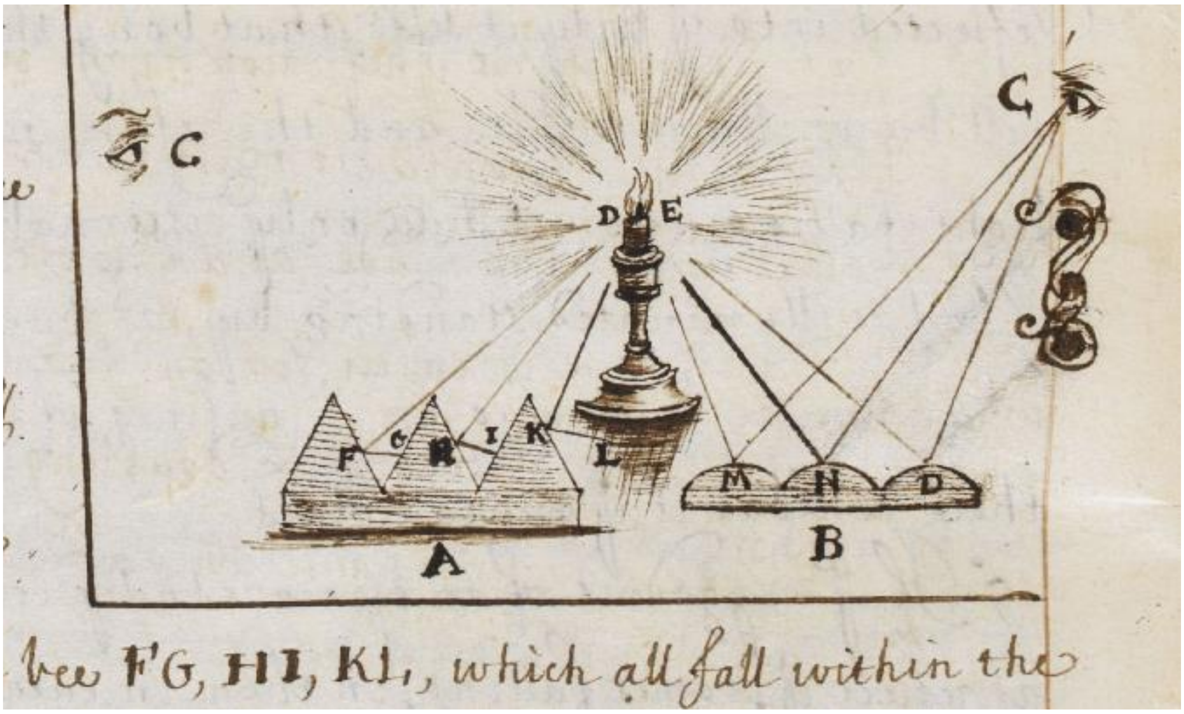


Fig. 3 Hobbes, *A Minute or First Draught of the Optiques*, 30^{v},
accessed via [www.bl.uk/manuscripts.](http://www.bl.uk/manuscripts)

Speaking generally, Hobbes's experimental work with a triangular prism could perhaps be viewed as a means of approaching an understanding of coloured light. He may have been prompted by the investigation described in *Les Météores*, but there is, in this case, no obvious polemical dimension to his discussion, either in the descriptions of his experimentation or in his cautiously expressed explanation of the phenomenon, according to which light is mixed in various ways in its refraction in and out of the glass[115]. Perhaps, then, the motivation underlying this example of practical work was

[115] Hobbes, *A Minute or First Draught*, 68$^{r\text{-}v}$.

similar to that evident in the suggestion that William, Earl of Newcastle, should repeat the experiment with a man's blood: it deserves to be known for the wonder[116].

There is, however, certainly a polemical context to the most dramatic example of experimental activity in Hobbes's optical work, that from which this chapter takes its title. The experiment in question appears not in the *Minute or First Draught*, but in the earlier Latin Optical Manuscript. The second of the four chapters in this draft treatise features a discussion of the second discourse of *La Dioptrique*, in which Descartes discusses the reflection and refraction of light with reference to a ball hit by a racket[117]. The comparison, as both Hobbes and Descartes identify, is helpful only up to a point: although light and a ball rebound from surfaces in the same way, the course they follow when they pass from one medium to another differs (light entering water from air moves towards the perpendicular, whereas a ball moves away from it)[118]. Both thinkers, however, seem to have considered the analogy valuable, with both devoting considerable attention to the movement of balls in particular circumstances.

Hobbes, for example, seems to have been particularly struck by a passage in *La Dioptrique*, in which Descartes considers the reflection of balls impacting bodies of water at oblique angles: "Now, the physical reason why a ball fired from the air into water at an angle of great obliquity will not penetrate, but be reflected, cannot be that which Descartes assigns on page 15 on the *Dioptrique*". He continues: "For, according to that, the ball will be reflected from the water and not penetrate at an angle of 45

[116] Letter 19, in Malcolm, ed., *The Correspondence of Thomas Hobbes*, vol. 1, 34. The wonder inspired by the rainbow is explored in Fisher, *Wonder, the Rainbow and the Aesthetics of Rare Experiences*, 33-56 and 87-120.
[117] Hobbes, 'Latin Optical Manuscript', 159-73. The second discourse of *La Dioptrique* is 93-105.
[118] For Hobbes's identification of this difference, see the 'Latin Optical Manuscript', 163. For Descartes's discussion of the point, see *La Dioptrique*, 102-3.

degrees. But I know, from certain experience, that a lead ball, fired from a gun at an elevation of five degrees and less, will penetrate the water"[119]. Descartes's discussion of the reflection of balls from bodies of water does not, however, appear on page fifteen of *La Dioptrique*, but on page nineteen[120]. On page fifteen, his subject is the reflection of a ball from the surface of the earth. Firstly, he establishes a distinction between the movement of an object and the direction of movement, which he calls its 'determination'. Then, he suggests that the determination of a ball can be described in terms of a vertical and a horizontal determination. The ground interrupts the vertical determination, apparently just by occupying the space below a certain level, but not the horizontal determination, and so the ball is reflected[121].

In comments set out earlier in the Latin Optical Manuscript, Hobbes dismisses Descartes's notion of determination as a "paralogism" and outlines an alternative explanation that centres on the resistance of the body that is struck, in this case the ground[122]. With his reference to a gun, he seems to be approaching the same question, although no direct connection is stated. Water, his argument implicitly runs, occupies the space below a certain level in the same way as the ground and, if Descartes's explanation were correct, a ball would be reflected in the same way. In fact, as his experiment highlights, a bullet will sometimes rebound from the surface of a body of water and sometimes not, depending on the angle at which it is fired.

[119] *Porro ratio Physica, quare in satis magna obliquitate, excussa pila tormento ab aere in aquam non penetrat, sed reflectatur, non potest esse ea quam assignat Cartesius Dioptricorum pag. 15. nam secundum eam reflecteretur pila ab aqua neque penetraret in obliquitate graduum 45 cum certissima experientia sciam pilam plumbeam excussari sclopetto, penetrare in elevatione quinque et minus graduum*, Hobbes, 'Latin Optical Manuscript', 165, my translation.
[120] Descartes, *La Dioptrique*, 99, C2^{r} in the original.
[121] Descartes, *La Dioptrique*, 93-6. The discussion of determination is on 94-5. For an overview of Descartes's work on reflection, see Sabra, *Theories of Light*, 69-92.
[122] Hobbes, 'Latin Optical Manuscript', 161-2. It is described as a "Paralogismus" on 161.

The same experiment appears elsewhere in the Latin Optical Manuscript, this time as part of a discussion of what *La Dioptrique* has to say about refraction. Descartes describes a ball striking a body that slows it by half (here the analogy is with a sheet) and suggests that the velocity is lost only from the vertical determination, not the horizontal[123]. The angle of refraction can be determined, he continues, by means of geometrical analysis (see figure 4). He suggests that, if the ball loses half its velocity, the line HF will be twice AH; he inserts a line FE, perpendicular to the surface of the water, which intersects the circle at I; this, he concludes, is the point at which the ball will end up[124]. Of course, in some scenarios the line FE will fall outside of the circle; in this case, he claims, the ball will be reflected, rather than refracted (see figure 5)[125].

[123] Descartes, *La Dioptrique*, 96-7. For an overview of Descartes's work on refraction, see Sabra, *Theories of Light*, 93-135.
[124] Descartes, *La Dioptrique*, 97-9.
[125] *Ibid.*, 99.

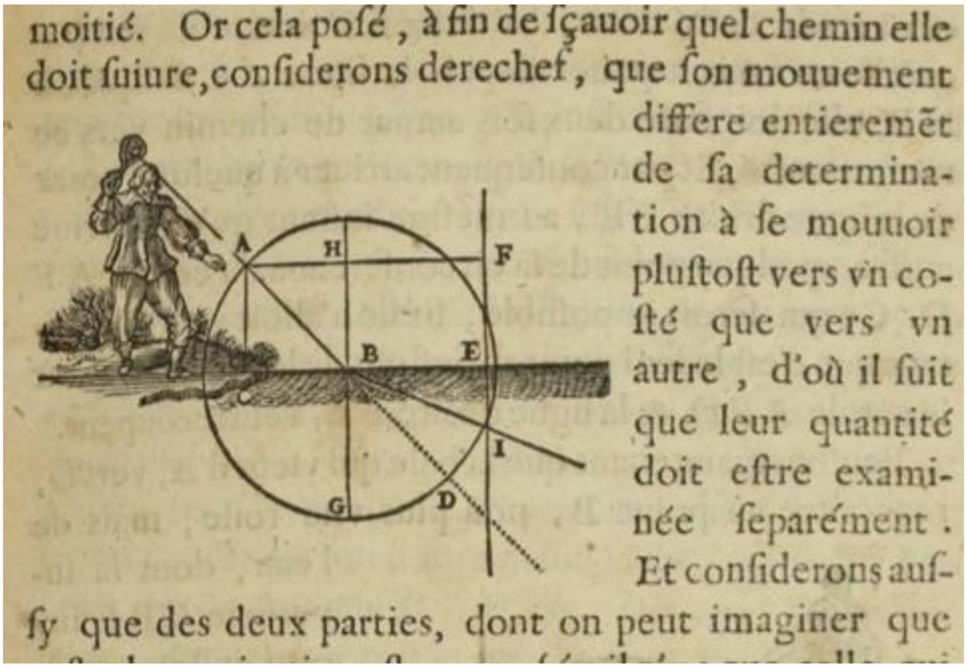

moitié. Or cela posé, à fin de sçauoir quel chemin elle doit suiure, considerons derechef, que son mouuement differe entieremẽt de sa determination à se mouuoir plustost vers vn costé que vers vn autre, d'où il suit que leur quantité doit estre examinée separément. Et considerons aussy que des deux parties, dont on peut imaginer que

Fig. 4 Descartes, *La Dioptrique*, in *Discours de la méthode*, C1r,

Bibliothèque Nationale de France RESM-R-76 – accessed via www.gallica.bnf.fr.

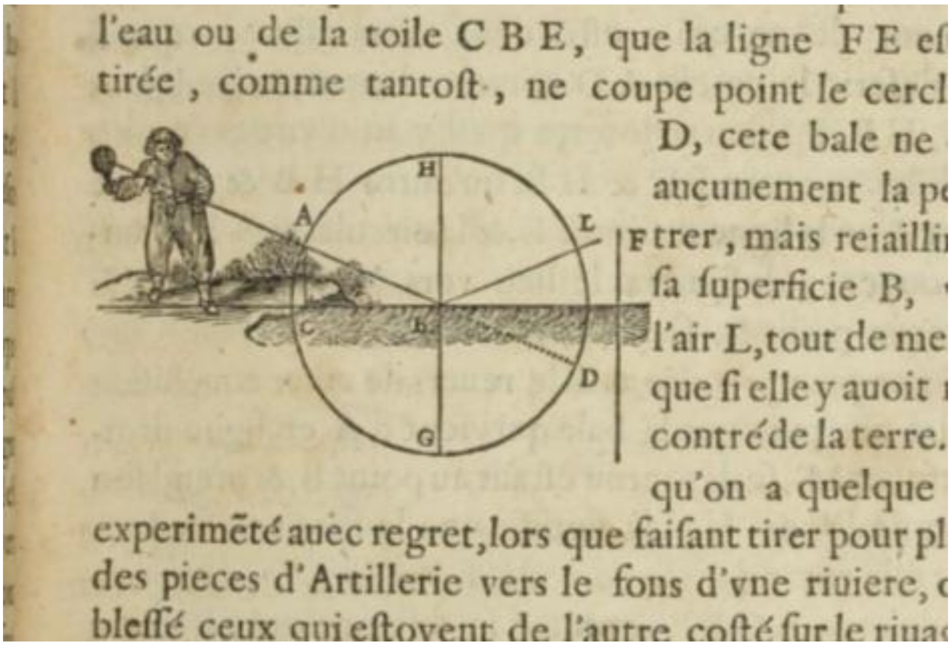

l'eau ou de la toile C B E, que la ligne F E es
tirée, comme tantost, ne coupe point le cercl
D, cete bale ne
aucunement la pe
trer, mais reiailli
sa superficie B,
l'air L, tout de me
que si elle y auoit
contré de la terre.
qu'on a quelque
experimẽté auec regret, lors que faisant tirer pour pl
des pieces d'Artillerie vers le fons d'vne riuiere,
blessé ceux qui estoyent de l'autre costé sur le riua

Fig. 5 Descartes, *La Dioptrique*, in *Discours de la méthode*, C2r,

Bibliothèque Nationale de France RESM-R-76 – accessed via www.gallica.bnf.fr.

For Hobbes, Descartes's geometry produces nonsensical results. If, he writes, a ball strikes a body that slows it by half at an angle of precisely 60 degrees, it will be refracted along the surface of the body[126]. He presumably chose the angle because of the ease of manipulating the figures involved. At 60 degrees, the line AH will be half AB, the radius of the circle; doubling it makes HF the length of the radius. In other words, the line FE will intersect the circle at the same point as the line CB. He has no qualms about hammering home the absurdity of the idea: "whatever the elevation, whatever the difference of the mediums, a ball will either penetrate or be reflected"[127]. Moreover, Hobbes continues, Descartes's geometry implies that a ball striking a body that slows it by a third (as, he suggests, water does) at an angle of 30 degrees will be reflected, rather than refracted[128]. Again, the selection of the angle in question is presumably for reasons of convenience. At 30 degrees the line AH will be $\sqrt{3}r/2$; tripling this leads to a result that is obviously larger than the length of the radius[129]. As Hobbes makes clear, the suggestion that an object striking at this angle will be reflected is contradicted by his experiences with a gun: "I myself have found that a bullet, fired from a gun at an elevation of five degrees, will penetrate and be completely submerged, and will be reflected at an elevation of two degrees"[130].

Interestingly, the idea of testing out Descartes's idea with a gun may have come from Descartes himself; after the claim in *La Dioptrique* that the ball will be reflected in

[126] Hobbes, 'Latin Optical Manuscript', 163-4.
[127] *nam in quacumque elevatione, et quacumque diversitate mediorum, proiecta pila vel penetrabit vel reflectetur*, Hobbes, 'Latin Optical Manuscript', 164, my translation.
[128] *Ibid.*, 164.
[129] This and the above calculation involve basic trigonometry, of the kind that Hobbes could have gained from Euclid, or while assisting in the surveying of the Chatsworth estates; for details of the latter, see Malcolm, *Aspects of Hobbes*, 93.
[130] *Nam ipse expertus sum pilam plumbeam emissam sclopetto, penetrare et penitus demergi, in elevatione quinque graduum; reflecti vero in elevatione duorum graduum*, Hobbes, 'Latin Optical Manuscript', 164, my translation.

cases where the line FE does not intersect the circle, he observes: “I have, unfortunately, experienced this, when we fired artillery into a river for fun and ended up injuring some people on the other bank”[131]. Whether or not this passage was a direct inspiration, Hobbes’s trials presumably took place at some point shortly after October 1637, when he received a copy of the *Discours de la méthode* from Sir Kenelm Digby. They may, indeed, have been conducted at one of the lakes that are just over an hour’s walk from Welbeck Abbey. His experiment had certainly been conducted by late 1640, when he confronted Descartes with the results in a letter sent via Marin Mersenne. This letter is now lost, but, in his reply of January 1641, Descartes writes: “it is not surprising that a ball of lead, fired with very great force from a gun, should have been seen to enter the water at an elevation of five degrees: for in those conditions it may not lose so much as one-thousandth of its velocity”[132].

There followed a lengthy and heated epistolary exchange, in which determination, reflection and refraction feature prominently, discussed for the most part in abstract terms[133]. The behaviour of balls as they strike bodies of water only reappears at the end of a letter sent by Hobbes in March, in which he points out to Mersenne a discrepancy between the description in Descartes’s text and the accompanying diagram (see above, figure 4): “But indeed, he himself knows what his intention was when he wrote, in the second discourse of his ‘Dioptrique’ (on p. 18), that he supposes the straight line HF to

[131] *Ce qu’on a quelque fois experimenté auec regret lorsque, faisant tirer pour plaisir des pieces d’Artillerie vers le fons d’vne riuiere, on a blessé ceux qui estoyent de l’autre costé sur le rivage*, Descartes, *La Dioptrique*, 99, my translation. John Cottingham, Robert Stoothoff and Dugald Murdoch translate ‘on’ with the impersonal ‘people’, 160, despite its first person use throughout *La Dioptrique*. Paul Olscamp uses the first person, 79, but I find his phrasing a little clumsy.
[132] *non mirum est quod expertus sit globum plumbeum, maximâ vj sclopeto emissum aquam Ingredj in eleuatione 5 graduum quia tunc forte non millesimâ suae velocitatis parte mulctabitur*, Letter 29, in Malcolm, ed., *The Correspondence of Thomas Hobbes*, vol. 1, 56, translated on 59.
[133] Letters 30, 32, 33 and 34, in Malcolm, ed., *The Correspondence of Thomas Hobbes*, vol. 1, 63-9, 87-9, 95-7 and 103-6. For an account of these discussions, see Giudice, *Luce e visione*, 55-69.

be twice AH, whereas in the accompanying diagram he makes it only slightly larger than AH itself". He continues: "In fact you can know the reason, Father, if you consider that if it had been done so, the line FI would have fallen outside the circle, and consequently a ball projected into water from an elevation equal to the angle ABC should have been reflected, which is contrary to experience"[134]. Descartes replies, somewhat defensively, that the error in the diagram was the printer's, not his. In any case, he continues: "when he says it is contrary to experience, he is completely mistaken; for experience varies in this matter, according to the variety of the objects which are thrown into the water, and the speed at which they move"[135].

In the Latin Optical Manuscript, then, Hobbes draws inferences from Descartes's discussions of reflection and refraction and describes the results of testing them experimentally, by firing a gun into a lake. The work also features his own theories; indeed, he presents an alternative explanation for the reflection of a ball from the surface of a body of water, in which he emphasises the resistance of the water[136]. His practical activity in this case, however, can best be viewed in a polemical context: the results of his experiment serve most obviously not to support his own ideas, but to bring those of Descartes crashing down to earth. This is, moreover, a point that he was clearly unafraid to make in correspondence with the great man himself.

---

[134] *Is verò quo animo in discursu secundo Dioptricorum pag. 18. supponit rectam HF esse duplam AH, in Schemate tamen apposito facit eam paulò majorem quam est ipsa AH, ipse scit. tu vero mi pater id scire potes, si consideres, quod ita faciendo, linea FI extra circulum cecidisset, et per consequens pila in aquam proiecta in eleuatione anguli ABC, deberet reflecti, quod est contra experientiam,* Letter 34, in Malcolm, ed., *The Correspondence of Thomas Hobbes*, vol. 1, 107, translated on 112. Malcolm highlights the correction of a spelling mistake.

[135] *Et en ce qu'il dit estre contre l'experience, il se trompe entierement; à cause qu'en cela l'experience varie, selon la varieté de la chose qui est iettée dans l'eau, & de la vitesse dont elle est meuë,* Letter 36, in Malcolm, ed., *The Correspondence of Thomas Hobbes*, vol. 1, 117, translated on 119.

[136] Hobbes, 'Latin Optical Manuscript', 165.

***

The image of Hobbes firing a gun into a lake is dramatic and does not easily cohere with the picture that emerges from current studies of his work in optics; in fact, the experiment has thus far been subjected to no sustained discussion[137]. One reason is perhaps the difficulty involved in accessing the Latin Optical Manuscript: the only published edition reproduces none of the original images, without which a reader will struggle to make sense of the text. The thought arises, however, that all of the evidence foregrounded in this chapter comes from material that has traditionally presented challenges for those seeking to access it, because it originally circulated in manuscript among members of the Cavendish circle. Neither the *Tractatus opticus*, published in 1644 by Mersenne, nor the discussion of optical matters included in *De corpore* and *De homine*, published in the following decade, feature anything resembling the comments about instruments and experiments that I have drawn from Hobbes's correspondence, the *Minute or First Draught*, and the Latin Optical Manuscript[138]. The incomplete nature of work on his optics, then, may not simply represent an oversight in the scholarship. It may also, in part, be the result of Hobbes's choices about the publication of his work. He seems to have been comfortable using instruments and conducting experiments, but he apparently had no desire to share details of this activity beyond trusted members of a close intellectual network.

[137] Noel Malcolm mentions the experiment in passing, as evidence for Hobbes's willingness to "dirty his hands in practical science"; see 'Hobbes and the Royal Society', 47.
[138] For the work published by Mersenne, see Hobbes, *Tractatus opticus*. The sections on optics in *De corpore* are 258-66 and 302-14. That in *De homine* is 7-87.

Robert Hooke Goes Back to Basics (and Draws the Same Conclusion)

Over the last quarter of a century, the reputation of Robert Hooke (1635-1703) has undergone something of a renaissance[1]. Whereas previous scholarship was, generally speaking, limited to E. N. da C. Andrade's 'Wilkins Lecture' and Margaret 'Espinasse's biography[2], the work of recent years includes at least three biographies[3], four volumes of essays[4], and book-length examinations of his architectural and geological activities[5]. In their introduction to a collection of essays, published in 1989, Michael Hunter and Simon Schaffer suggested that the reasons for his neglect at that point included his "diversity" and his involvement in "applied science"[6]. Times have certainly changed. Stephen Inwood's recent biography successfully conveys the range of Hooke's interests, in one place by describing month by month his activity in the year 1674[7]. Meanwhile, a number of studies have examined his practical work in such fields as acoustics, architecture, astronomy, horology, medicine, navigation and optics[8].

---

[1] For a consideration of Hooke's posthumous reputation, see Jardine, 'Robert Hooke: A Reputation Restored'. See also Michael Cooper and Michael Hunter's introduction to *Robert Hooke: Tercentennial Studies*.
[2] Andrade, 'Wilkins Lecture: Robert Hooke', and 'Espinasse, *Robert Hooke*.
[3] Chapman, *England's Leonardo*, Inwood, *The Man Who Knew Too Much*, and Jardine, *The Curious Life*.
[4] Bennett, Cooper, Hunter and Jardine, eds., *London's Leonardo*; Cooper and Hunter, eds., *Robert Hooke: Tercentennial Studies*; Hunter and Schaffer, eds., *Robert Hooke: New Studies*; and Kent and Chapman, eds., *Hooke and the English Renaissance*.
[5] Cooper, *Hooke and the Rebuilding of London*, and Drake, *Restless Genius*.
[6] Hunter and Schaffer, 'Introduction', in *Robert Hooke: New Studies*, 1-2.
[7] Inwood, *The Man Who Knew Too Much*, 191-9.
[8] For studies of his work in these sometimes overlapping fields, see Beier, 'Experience and Experiment'; Bennett, 'Hooke's Instruments' and 'Instruments and Ingenuity'; Chapman, *England's Leonardo*, 55-152; Cooper, *Hooke and the Rebuilding of London*; Gouk, 'The Role of Acoustics'; Heyman, 'Hooke and Bedlam'; Iliffe, 'Material Doubts'; Jardine, 'Hooke the Man'; Nakajima, 'Hooke as an Astronomer'; Simpson, 'Hooke and Practical Optics'; and Stoesser, 'Hooke's Montagu House'. For older overviews of his practical activities, see Bennett, 'Hooke as Mechanic and Natural Philosopher', Centore, *Hooke's Contributions to Mechanics*, and Westfall, 'Robert Hooke, Mechanical Technology and Scientific Investigation'.

Of course, Hooke's practical work in optics was never really lost from historical view, due to the enduring appeal of his most famous work, *Micrographia*. In the published version of a lecture given in 1965 to celebrate the tercentenary of the book's first publication, A. Rupert Hall describes it as "one of the major English contributions to seventeenth-century science". He continues: "in particular, it was the first book in the history of science to treat microscopy as a serious aspect of biology"[9]. The 'Hooke Renaissance', then, lies not simply in the new attention that his practical work is receiving, but also in the new attitude with which it is examined. Hall's conception of the significance of *Micrographia* seems to rest on the developments in biology that resulted from Hooke's advances in microscopy, rather than on those advances themselves. In a more recent essay, by contrast, Jim Bennett notes that his "talent for devices of investigation and application" is now esteemed "on [its] own terms"[10].

The fundamental claim in what follows, however, is that the new attitude to Hooke remains, to some extent, simplistic. The implicit assumption in all the recent scholarly activity seems to be that his practical work was simply the natural expression of his practical gifts: Hooke did practical work, the thought seems to go, because he was a practical man. Of course, he obviously was a man of considerable practical talents, but there is also, to my mind, some value to be had from thinking about the uses to which his talents were put. In line with the approach pursued throughout the thesis, my goal here is to examine the deployment of his ability with instruments and experiments, with the idea that his practical work may, in part, have been valuable for its capacity to persuade an audience that another philosopher's ideas were wrong.

---

9 Hall, *Hooke's Micrographia*, 31.
10 Bennett, 'Instruments and Ingenuity', 65.

The first section of the chapter focuses on Hooke's place in the early Royal Society, charting his rise to prominence in the years before and after he was appointed Curator of Experiments in 1662. The second discusses the theories of light, colour and inflection that are articulated in *Micrographia*, showing that his ideas build on and, in some cases, celebrate the activities of fellow members of the Royal Society, particularly Robert Boyle. Finally, the third describes his use of practical work as a means of defending his theory of light, after it was, in his mind, the subject of an attack from Isaac Newton. Although in what follows Hooke remains a natural philosopher with an evident genius for practical work, my hope is that he emerges as a man capable of harnessing his gifts to particular, sometimes polemical ends.

"I endeavour to be conversant in all kinds of Experiments": Hooke and the Early Royal Society

On 28 November 1660, a group of men met at Gresham College in London and agreed to form an intellectual club, which soon became known as the Royal Society[11]. Robert Hooke was not one of them. In fact, despite his connections with such founding Fellows as John Wilkins, Robert Boyle and Christopher Wren, dating to his time in Oxford in the 1650s[12], he is almost totally unmentioned in the body's records before his election as Curator of Experiments in November 1662. Most accounts of his relationship with the Society start with this election[13], although in her biography Lisa Jardine has suggested that he was probably involved before[14]. Here, I endeavour to support her suggestion with a picture of his place in some of the practical work carried out in the first two years of the organisation's existence. If he was, as I suggest, involved in this activity, his name went unrecorded, a fact that is not necessarily surprising, given his comparatively low social status[15]; his absence from the archives, however, does mean that any conclusions must be speculatively phrased.

---

[11] A memorandum relating to the meeting, including a list of those present, is recorded in volume one of the Journal Book, Royal Society MS JB0/1, 1-2. For the founding of the Royal Society, see Hall, *Promoting Experimental Learning*, 9; Hunter, *Establishing the New Science*, 1-2; and Purver, *The Royal Society*, 128-9. See also Birch, *The History of the Royal Society*, vol. 1, B2^{r-v}. Many, but not all, of the documents that I will be referring to in this chapter and the following one appear in the volumes of Birch's work; for the sake of simplicity, I will quote from the originals throughout, but I will provide enough information to allow cross-referencing.

[12] For Hooke's time in Oxford, see Inwood, *The Man Who Knew Too Much*, 18-24, and Jardine, *The Curious Life of Robert Hooke*, 63-82. For an overview of the natural philosophical community in the town in this period, see Frank Jr., *Harvey and the Oxford Physiologists*, 43-89.

[13] See, for example, Cooper, 'Hooke's Career', 10-11; 'Espinasse, *Robert Hooke*, 43; and Inwood, *The Man Who Knew Too Much*, 30.

[14] Jardine, *The Curious Life of Robert Hooke*, 91-7.

[15] For studies that highlight Hooke's comparatively low social status, see Pumfrey, 'Ideas above his Station', and Shapin, 'Who Was Robert Hooke?'. For a critique of Shapin's essay, see Feingold, 'Robert Hooke: Gentleman of Science'.

If Hooke was a silent feature of early Royal Society activity, his presence is an obvious factor in his subsequent election as Curator of Experiments. Once elected, as will be seen, he rapidly came to occupy a prominent position in the body's regular meetings, a rise that I attribute, in part, to the dramatic spectacles that he was able to provide on an almost weekly basis. His ability in practical matters was of course useful, but my suggestion in this section (involving a metaphor with appropriately mechanical origins) is that he leveraged his talents to make himself indispensable.

As Lisa Jardine has highlighted, Hooke had almost certainly performed experiments at the Royal Society before he was elected to the Curatorship[16]. One of the body's early showpieces was Robert Boyle's air-pump, a device designed to evacuate the air from a glass container, described in his *New Experiments Physico-Mechanicall, Touching the Spring of the Air* of 1660[17]. The pump was exhibited at meetings in February 1661 and January 1662 before, respectively, the Danish and Genoese ambassadors[18]. At a gathering on 7 May 1662, attended by Prince Rupert of the Rhine, a number of Fellows placed their arms inside it, apparently causing a sensation[19]: John Evelyn provides a vivid description in his diary and the following week John Wilkins, who seems to have been absent, requested that the experiment be repeated[20].

---

[16] Jardine, *The Curious Life of Robert Hooke*, 94-5.
[17] Boyle, *Spring of the Air*, 160-3.
[18] The meetings were held on 13 February 1661 and 29 January 1662; see Royal Society MS JBO/1, 10 and 47.
[19] Royal Society MS JBO/1, 58. Prince Rupert's presence is mentioned in John Evelyn's diary; see de Beer, ed., *The Diary of John Evelyn*, vol. 3, 318.
[20] For the account in Evelyn's diary, see de Beer, ed., *The Diary of John Evelyn*, vol. 3, 318; for Wilkins's request, see the minutes of the meeting held on 14 May, Royal Society MS JBO/1, 59-60, at 60.

Jardine suggests that such experimental *coups de théâtre* were carried off by Boyle's collaborator in the invention of the device, Robert Hooke[21]. In general, the older, aristocratic man was well placed to play a significant part in his colleague's involvement in early Society activity[22]. Here, Hooke's role is that of the necessary, albeit unmentioned technician, who ensures that an important spectacle goes to plan[23]. But Boyle may also have facilitated his place in a more creative task.

A minute from the first formal meeting of the Society, on 5 December 1660, records the preparation of "some questions, in order to the triall of the Quicksilver Experiment uppon Tenariff"[24]. The note alludes to a famous experiment, first mentioned by the Italian natural philosopher Evangelista Torricelli in a letter of June 1644[25]. Torricelli describes filling a tube with mercury, blocking one end, inverting it, placing it in a bowl of mercury, and releasing the blockage. The mercury in the tube sinks a certain distance, depending on the pressure of the air on that in the bowl[26]. It leaves a space, the 'Torricellian vacuum', the nature of which was hotly debated in the period[27].

The inspiration for trialling the experiment on the island of Tenerife, the peak of which was at this time commonly thought to be among the highest in the world[28], was probably

[21] The invention of the air-pump is attributed to Hooke in Boyle, *Spring of the Air,* 159.
[22] For a sense of Boyle's importance for the early Royal Society, see Hunter, *Boyle: Between God and Science,* 131-2.
[23] For a discussion of the place of 'invisible technicians' in experimental work of the period, see Shapin, *A Social History of Truth,* 355-407.
[24] Royal Society MS JBO/1, 3.
[25] Evangelista Torricelli to Michelangelo Ricci, in Galluzzi and Torrini, eds., *Opere*, vol. 1, 122-3. For an overview of the experiment, see Middleton, *The History of the Barometer*, 19-32.
[26] Torricelli ascribes the phenomenon to "la gravità dell'aria" (the weight of the air) in Galluzzi and Torrini, eds., *Opere*, vol. 1, 122.
[27] For an overview of debates about the 'Torricellian vacuum', see Shapin and Schaffer, *Leviathan and the Air-Pump,* 41-2.
[28] For relevant descriptions of Tenerife that place its peak among other high mountains, see Bacon, *Novum organum*, 220-2, and Wilkins, *Concerning a New World,* K2[r]. A discussion of the height of the peak appears in Boyle, *A Continuation,* 97-100.

a discovery mentioned in Robert Boyle's *Spring of the Air*: in 1648, the French philosopher Blaise Pascal had reported that the mercury sank further at the top of the Puy de Dôme, a mountain in central France, than at the bottom[29]. If Boyle's work on air pressure meant that he was the obvious candidate to sketch out a similar experiment for Tenerife, he may have passed the job on to Hooke. Among the 'Hooke papers' in the Royal Society archive is an undated note containing suggestions about conducting the Torricellian experiment, alongside measurements with a weather glass and a thermometer, at the bottom, middle and top of an unspecified mountain[30]. Although there is no reference to Tenerife, Hooke's comment certainly corresponds to the first of the questions entered into the Society's Register Book in January 1661: "Trie the Quicksilver Experiment at the Top & at severall other ascents of the Mountain […] and observe at the same time the temperature of the air, as to heat & cold by a weather glasse; & as to moisture & dryness with a hydroscope"[31].

A remark in Boyle's *A Continuation of New Experiments Physico-Mechanical*, published in 1669, suggests that the experiment never took place[32], but Hooke appears to have remembered his contribution to some of the Society's earliest business, although he confused it with activity of a slightly later date. In his *Lectures de potentia restitutiva, or of Spring*, published in 1678, he describes an investigation into the

[29] For an overview of the experiment, see Shea, *Designing Experiments*, 106-16. It is mentioned in Boyle, *Spring of the Air*, 169. For the reception of Pascal's work on the void in England, see Barker, *Strange Contrarieties*, 41-7.
[30] Item 14, Royal Society MS Cl.P/20, 23. Volume 20 of the Classified Papers contains material associated with Hooke, arranged chronologically; this undated item appears with similar work relating to the Torricellian experiment from 1663, perhaps based on the assumption that his involvement with the Society post-dated his election as Curator of Experiments.
[31] 'Questions Propounded and agreed vppon to be sent to Tenariff', dated 2 January in volume one of the Register Book, Royal Society MS RBO/1, 1-2; the quote is from 1.
[32] Boyle writes: "I have been solicitously endeavouring to get the Torricellian Experiment tried upon the Pic of Teneriff, but hitherto I have had no Account of the success of my Endeavours"; see *A Continuation*, 96.

attraction of objects towards the centre of the earth as they are removed further from it: "And propounded it as one of the Experiments to be tried at the top of the Pike of *Teneriff*, and attempted the same at the top of the Tower of St. *Pauls* before the burning of it in the late great Fire; as also at the top and bottom of the Abby of St. *Peters* in *Westminster*"[33]. There is nothing resembling an investigation into gravity in the questions to be sent to Tenerife, but the subject does appear alongside the Torricellian experiment in the reports of trials conducted at St Paul's and Westminster Abbey in the early 1660s[34]. It is not hard to think that, writing at a distance of 15 years from the work that he was describing, Hooke may have mixed up some of the details.

If Hooke was, as I am suggesting, involved in preparing proposals for Tenerife, it seems likely that Robert Boyle played a relatively direct role in securing his participation. When it comes to other possible examples of Hooke's involvement in Royal Society activity, Boyle's place is less obvious, but by no means less significant: the excitement caused by some of the experiments related in the *Spring of the Air* may have focussed attention on the man known to have been a valuable contributor to the book.

At some point in the summer of 1661, the physician and Fellow of the Royal Society Jonathan Goddard conducted a number of trials involving water in a very long tube[35].

---

33 Hooke, *Lectures de potentia restitutiva*, B3^{v}.

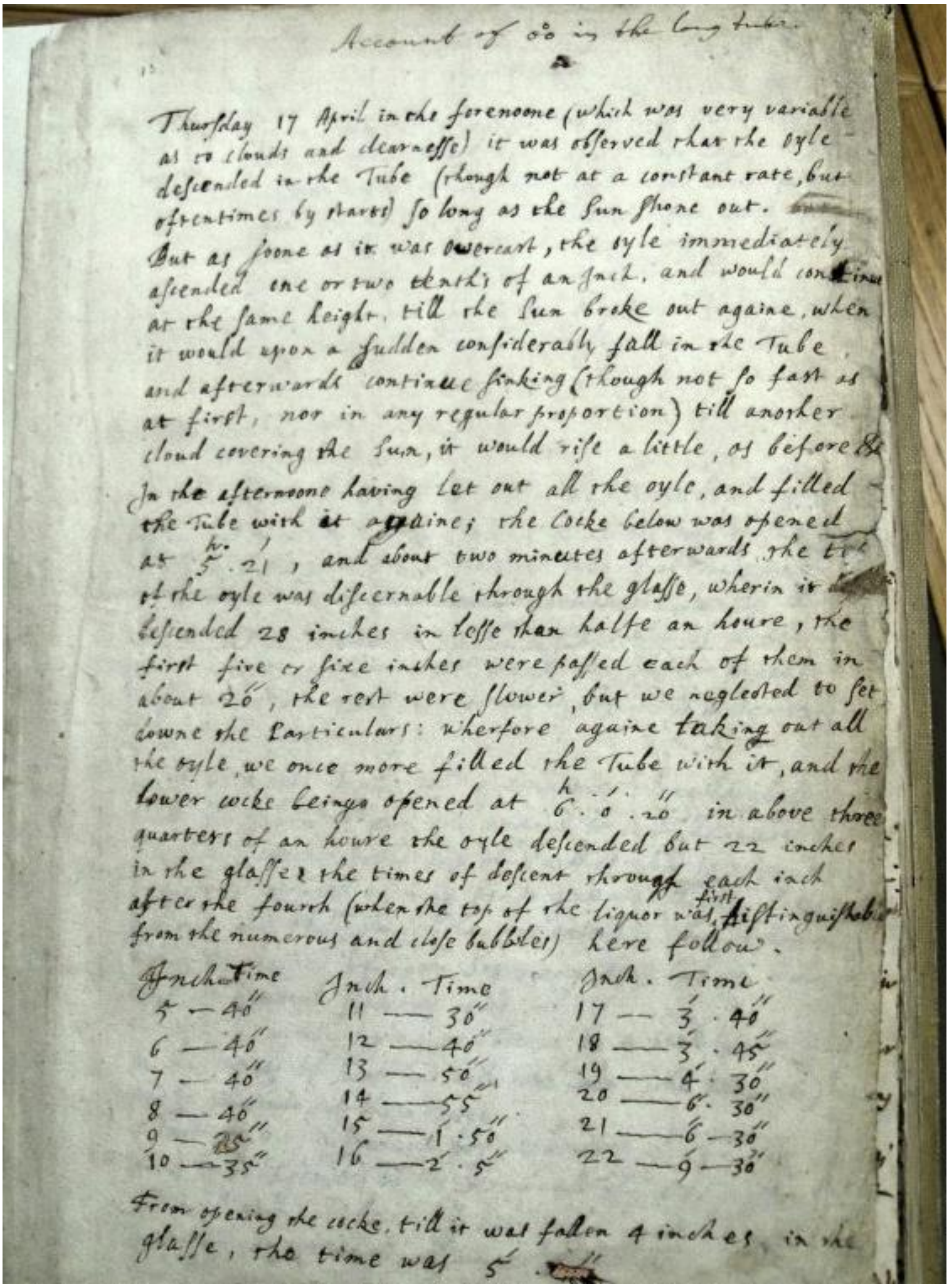
34 Hooke was appointed the 'curator' of experiments at St Paul's and Westminster Abbey at a meeting held on 17 December 1662; see Royal Society MS JBO/1, 120-2, at 122. The results were recorded as 'Of the difference of Gravity by removing the Body further from the Surface of the Earth upwards', in volume two of the Register Book, MS RBO/2(i), 78-80. On 24 August 1664, he was ordered to try the 'Torricellian experiment' at St. Paul's; see MS JBO/2, 123. He reported the results on 7 September; see 127-8, at 127.

35 At a meeting on 4 September 1661 Goddard was encouraged to bring in the results of his experiments in writing; see Royal Society MS JBO/1, 30-2, at 31. He eventually did so on 17 August 1664; see MS JBO/2, 120-4, at 120. The results were recorded as 'Observations upon the Experiments of Several Liquors in a Tube of about 36. Foot in Length, erected perpendicularly' in MS RBO/3, 60-1. For an overview of his life and career, see Oster, 'Goddard, Jonathan'.

His work may have been inspired by the report in the *Spring of the Air* of another discovery by Pascal: the Torricellian experiment can be replicated with water, in a tube that is 32 feet long[36.] At a meeting held on 9 April 1662, members of the Society urged Goddard to repeat his experiments, this time with milk and oil[37]. At this point, he was joined by another Fellow, Lawrence Rooke: at a meeting two weeks later, the latter read a description of the rising and sinking of a certain quantity of oil as the weather changed[38]. The account, which was entered into the Society's Register Book, is attributed to Goddard and Rooke, but a draft lies among Hooke's papers, suggesting that he may also have been involved, in some unacknowledged way[39]. Compared with his other papers, the piece is written in an unusually clear hand (see figure 1). It is worth considering that the manipulation of the technology may have required the touch of Boyle's skilful collaborator, who carefully wrote up a description for Rooke to read aloud and then oversaw its translation into the Register Book.

---

[36] Boyle, *Spring of the Air*, 205. For an overview of Pascal's work with long tubes, see Shea, *Designing Experiments*, 44-6.
[37] Royal Society MS JBO/1, 54-5, at 54.
[38] Royal Society MS JBO/1, 55-6, at 56. The account was entered into the Register Book as 'An Account of an Experiment made with Oyle in the Long Tube'; see MS RBO/1, 165-6. For a survey of Rooke's life and career, see Keller, 'Rooke, Lawrence'.
[39] Item 13, Royal Society MS Cl.P/20, 22^{r-v}.



Account of oo in the long tube.

Thursday 17 April in the forenoone (which was very variable as to clouds and clearnesse) it was observed that the oyle descended in the Tube (though not at a constant rate, but oftentimes by starts) so long as the Sun shone out. But as soone as it was overcast, the oyle immediately ascended one or two tenth's of an Inch, and would continue at the same height, till the Sun broke out againe, when it would upon a sudden considerably fall in the Tube, and afterwards continue sinking (though not so fast as at first, nor in any regular proportion) till another cloud covering the Sun, it would rise a little, as before &c.

In the afternoone having let out all the oyle, and filled the Tube with it againe; the Cocke below was opened at $5^{h}.21'$, and about two minutes afterwards the top of the oyle was discernable through the glasse, wherin it descended 28 inches in lesse than halfe an houre, the first five or sixe inches were passed each of them in about 26'', the rest were slower, but we neglected to set downe the Particulars: wherfore againe taking out all the oyle, we once more filled the Tube with it, and the lower cocke being opened at $6^{h}.0'.20''$ in above three quarters of an houre the oyle descended but 22 inches in the glasse: the times of descent through each inch after the fourth (when the top of the liquor was first distinguishable from the numerous and close bubbles) here follow.

Inch	Time	Inch	Time	Inch	Time
5	40''	11	36''	17	3'.40''
6	40''	12	40''	18	3'.45''
7	40''	13	50''	19	4'.30''
8	40''	14	55''	20	6'.30''
9	35''	15	1'.50''	21	6'.30''
10	35''	16	2'.5''	22	9'.30''

From opening the cocke, till it was fallen 4 inches in the glasse, the time was 5'. [illegible]''

Fig. 1 Item 13, Royal Society MS Classified Papers, volume 20, 22r.

At about the same time, another phenomenon, also described in the *Spring of the Air*, was intriguing the Society's Fellowship: the capillary action of liquids in small tubes[40]. The subject was raised on 6 March 1661 and a fortnight later Nathaniel Henshaw, another physician and early member of the organisation, made several experiments with water, ethanol, rose water and hydrochloric and sulphuric acid[41]. On 10 April, as Lisa Jardine has highlighted, the discussion for the following meeting was ordered to be the account of the phenomenon included in "M^r Hookes little booke"[42]. The lengthy title of this little treatise, Hooke's first venture into print, clearly aligns it with the work described in the *Spring of the Air*, but if readers were in any doubt about the relationship between the author and Robert Boyle, it is dispelled by the dedicatory epistle, in which the former styles himself as a pagan worshiper, presenting his god with the fruits of his labour: "I must therefore with the *Persian* offer to you, as he to the Sun, what he believes himself to have received from it"[43].

The text presents a cautious explanation for the capillary action of water, according to which it has a greater 'congruity' to glass than water[44]. It concludes with general comments about the value of experimentation; Hooke writes:

> I would not be thought guilty of that Errour, which the thrice Noble and Learned *Verulam* [Francis Bacon] justly takes notice of, as such, and calls *Philosophiæ Genus Empiricum, quod in paucorum Experimentorum Angustiis & Obscuritate*

[40] Boyle, *Spring of the Air*, 252-3. Boyle ascribes the observation of the phenomenon to "some inquisitive French Men", 252; presumably these are the members of the Académie de Montmor described in Millington, 'Theories of Cohesion', 257-8.
[41] Royal Society MS JBO/1, 11 and 12. For an overview of the life and career of Nathaniel Henshaw, see Goodwin, 'Henshaw, Nathaniel'.
[42] Royal Society MS JBO/ 1, 15; see Jardine, *The Curious Life of Robert Hooke*, 93.
[43] Hooke, *An Attempt for the Explication*, A2^r-A3^v, at A2^v.
[44] *Ibid*., A6^v-C8^r.

fundatum est [the empirical kind of philosophy that is based on the darkness and narrowness of a handful of experiments] [...] But on the contrary, I endeavour to be conversant in all kinds of Experiments, and all and every one of those Trials, I make the standards (as I may say) or Touchstones by which I try all my former Notions, whether they hold not in weight and measure and touch, *&c*.[45]

This comment does not simply make a claim about Hooke's skill in performing experiments. This is a statement about the importance of experimentation for the advancement of knowledge. It is difficult to know the extent to which it was aimed at members of the Royal Society, but it seems safe to say that they would have appreciated both the emphasis on experiments and the invocation of Francis Bacon[46].

If Hooke's advocacy of practical work in print and the deployment of his skills in Royal Society experiments had the goal of securing an enhanced place in the organisation, his efforts did not go unrewarded. The minutes of a meeting held on 5 November 1662 include a suggestion by the founding member Sir Robert Moray: that the group elect a Curator, who would agree to carry out three or four experiments at each of the Society's weekly meetings. The man selected for the position was, in the light of the work that I have tentatively reconstructed, an obvious choice: Robert Hooke[47].

Hooke was never able to meet the expectation that he perform three or four experiments a week, although he wasted no time in trying. At the meeting after the confirmation of

---

[45] *Ibid.*, C8$^{r\text{-}v}$. Hooke's quote is taken from Bacon, *Novum organum*, 98.
[46] For the importance of experimentation for the early Royal Society, see Hall, *Promoting Experimental Learning*, 9-23; for the place of Francis Bacon, see Purver, *The Royal Society*, 20-62.
[47] Royal Society MS JBO/1, 101-3, at 103. The award of the role to Hooke was written in at a later date, in what looks like his own hand. For a survey of the life and career of Sir Robert Moray, see David Stevenson's introduction to the *Letters of Sir Robert Moray*.

his role, he broke several glass bubbles by heating the air inside them[48]. On 3 December, he weighed air of different densities[49]. On 7 January, he measured the weight of warm and cold water and noted the differing refraction of light[50]. All of this activity was built on material included in the *Spring of the Air*[51], but it is nevertheless worth stressing the numbers: clearly, Hooke was extremely efficient when it came to devising and conducting experiments before the Society.

Of course, to focus on the numbers is to overlook some of the theatrical aspects of his place in the meetings following his election. On 28 January 1663, for example, he "made the Experiment, of shutting up, in an oblong-glasse, a burning lampe, and a Chick". The question under investigation is the consumption of air, by burning and by animal respiration, but there is an obvious drama to be had from awaiting the results: "the Lamp went out within two minutes, the Chick remaining alive, and lively enough"[52]. At the next meeting, he conducted a similar experiment, but one with a competitive edge: measuring how long the Society's Fellows could breathe the same air in a bag. The physician Christopher Merret managed "76 times in three minutes"; Hooke's own effort is, by comparison, risible: "19 times in 1 1/4 minute"[53].

Perhaps the most dramatic event of these months was recorded in the minutes of a meeting held on 1 April: "The Experiment of Exhausting the Air from a Fish in water,

---

[48] Royal Society MS JBO/1, 106-10, at 107. The results were recorded as 'A Breif Account of the Experiments try'd with Glasse Balls', in MS RBO/2(i), 78-80. His place was confirmed on 12 November; see MS JBO/1, 103-6, at 103.
[49] Royal Society MS JBO/1, 114-7, at 116. The results were recorded as 'An Account of the Rarefaction of the Air', in MS RBO/2(i), 55-8.
[50] Royal Society MS JBO/1, 126-9, at 127. The results were recorded as 'An Account of an Experiment touching the differing weight of cold and warme water', in MS RBO/2(i), 103-6.
[51] See Boyle, *Spring of the Air*, 180-1 and 254-5.
[52] Royal Society MS JBO/1, 135-7, at 135.
[53] Royal Society MS JBO/1, 137-9, at 138. For an overview of the life and career of Christopher Merret, see Allen, 'Merret, Christopher'.

was tryed in the Engine [the air-pump]; whereby the Fish (which was a Tench) was put into much disorder, and boyed up to the upper part of the water, when he would sink; his eyes also swelling and standing out"[54]. The experiment was repeated on 13 May with a carp[55]. According to the account entered into the Register Book: "being taken out of the Vessel it was very dexterously and carefully opened by D^{r}. Clarke, who found that the Bladder was manifestly broken in two places"[56]. The likely inspiration for this lethal use of the air-pump is an experiment conducted by the French natural philosopher Gilles de Roberval, in which a carp's swim bladder was seen to inflate when suspended in the Torricellian vacuum[57]. The Royal Society investigation supports the Frenchman's observation – the bladder seems to have inflated to the point of bursting – but using an entire live carp is clearly a more spectacular set-up.

At about the same time, Hooke was providing attendees of Royal Society meetings with other fascinating spectacles, this time the result of his skilful manipulation of instruments. At a meeting on 25 March 1663, he was urged to pursue some observations with a microscope, which could then be published[58]. Again, he did not take long to deliver. On 8 April he exhibited a drawing of moss[59]. The following week he showed

[54] Royal Society MS JBO/1, 154-6, at 154. The original features a deletion that I have not included. A description of the experiment was recorded as 'An Account, brought in by D^{r}. Croon. Of a Tench tryed in the Exhausting Engine', in MS RBO/2(i), 224. For an overview of the life and career of the physician William Croone, see Martensen, 'Croone, William'.
[55] Royal Society MS JBO/1, 168-170, at 170.
[56] 'An Account of what happened to a Carpe included in a Vessel of Water out of which the Air was pretty well Exhausted', dated 20 May in Royal Society MS RBO/2(i), 224-5; the quote is from 225. For an overview of physician Timothy Clarke's life and career, see Goodwin, 'Clarke, Timothy'.
[57] The experiment is mentioned in Boyle, *Spring of the Air*, 174. For an overview, see Middleton, *The History of the Barometer*, 49-50.
[58] Royal Society MS JBO/1, 149-53, at 152. Drawings from this period in British Library MS Add. 57495 have been attributed to Hooke by Janice Neri; see 'Some Early Drawings'. The project was originally Christopher Wren's. The minutes of a meeting held on 1 May 1661 charge him "to make a Globe of the Moon, and to describe the bodies of severall Insects, as he has already begun"; see MS JBO/1, 18-20, at 18. Lisa Jardine has suggested that Wren and Hooke worked together, before the latter took the project over; see *On a Grander Scale*, 276-8.
[59] Royal Society MS JBO/1, 157-8, at 157.

one of a piece of cork and one of some Ketton stone[60]. In the following months, many of his sketches were of an entomological or arachnological character. On 6 May, for example, he brought in "a Microscopical Observation of a female Gnat, discerned from the male, by the bignesse of her Belly, that of the male being thin and Lank, and the male having also a Tuft"[61]. On 19 August, he showed a "long-legged Spider; having two Eyes fixed on his back, and standing out upon a stemme"[62].

The selection of objects for examination through the microscope no doubt owes something to intellectual curiosity, but the number of insects and arachnids suggests that Hooke may also have been seeking to provide images of a spectacular nature. It is certainly not difficult to imagine how engaging members of the Royal Society would have found these drawings. In fact, on 26 May 1663 an unnamed Fellow, probably the poet and politician Edmund Waller, felt moved to charge him: "to look upon sage [...] and to observe, whether there did Lurke, any little Spiders in the Cavityes of the leaves, that might make them noxious"[63]. In this case, Hooke may well have regretted the interest that he had aroused in his audience: on 10 June he reported that had seen none, but, at the following meeting, he was urged to continue his investigations[64].

The establishment of Hooke's place within the Royal Society was remarkably swift. In the space of a few years, he seems to have risen from an uncredited participant in other people's experiments to a fixture of the body's weekly meetings; his importance was

[60] Royal Society MS JBO/1, 159-61, at 159.
[61] Royal Society MS JBO/1, 166-8, at 167. The original has an intralinear insertion.
[62] Royal Society MS JBO/1, 212-4, at 213.
[63] Royal Society MS JBO/1, 175-81, at 175. The minutes of the previous meeting, held on 20 May, report: "Mr. Waller alledged, that it had been observed by a Microscope, that Sage hath little Cavityes, used to be filled with Small Spiders; and that this was the cause, which made the plant noxious, if not well washed"; see 170-74, at 171. The original features an intralinear insertion. For Waller's life and career, see Chernaik, 'Waller, Edmund'.
[64] Royal Society MS JBO/1, 185-8 and 188-92, at 186 and 189.

confirmed on 3 June 1663, when, at a meeting of the Council, he was officially elected as a Fellow of the Society[65]. His advancement was, of course, due to his practical gifts, but a significant factor, to my mind, is the extent to which he was willing and able to leverage those gifts. When it came to electing a Curator of Experiments, the contributions to early Society business that I have ascribed to him would have made him the obvious choice; meanwhile, in the meetings that followed, his provision of dramatic experimental and pictorial spectacles served to make him indispensable.

[65] See the first volume of Council Minutes, Royal Society MS CMO/1, 8-9, at 9.

“[F]irst shewn to the *Royal Society*”: Optical Theories in *Micrographia*

In 1665, Robert Hooke’s *Micrographia* was published. Like Robert Boyle’s air-pump, the work can be viewed as a showpiece for the early Royal Society; indeed, in a study of Hooke’s natural philosophy, Michael Hunter has summed up the ethos of its publication: “*Micrographia* was as much a Royal Society book as Hooke’s own, since it was seen by the Society as exemplifying the empirical method by which it set such store”[66]. The most obvious exemplification of the Society’s method comes in the form of a series of dramatic microscopic images, which, unsurprisingly, have attracted the lion’s share of scholarly attention[67]. The book also, however, contains lengthy theoretical passages, which are hardly empirical in character and which, for that very reason, seem to have attracted the censure of some early Fellows. When Hooke came to write a prefatory address to the Society, he apparently felt the need to adopt an apologetic tone; perhaps in response to complaints about the book’s contents, he acknowledges: “there may perhaps be some *Expressions*, which may seem more *positive* then YOUR Prescriptions will permit”. He continues: “though I desire to have them understood only as *Conjectures* and *Quæries* […] yet if even in those I have exceeded, ’tis fit that I should declare, that it was not done by YOUR Directions”[68].

Among the conjectures that Hooke may have had in mind are his discussions about the nature of light, colours, and what is referred to in the text as ‘inflection’. These discussions have been placed within the context of an optical tradition that also includes

[66] Hunter, ‘Hooke the Natural Philosopher’, 111; see also 124-31.
[67] See, for example, Doherty, ‘Discovering the ‘True Form’’, Harwood, ‘Rhetoric and Graphics in *Micrographia*’, Jack, ‘A Pedagogy of Sight’, and Neri, *The Insect and the Image*, 105-38. For an extended discussion of natural philosophical image-making practices of the period, see Hunter, *Wicked Intelligence*.
[68] Hooke, *Micrographia*, A2^{v}.

the work of Thomas Hobbes and René Descartes[69], but they have not been set against what, given Michael Hunter's statement about the ethos underlying the publication of *Micrographia*, looks like a more obvious backdrop: the contemporary activity of the Royal Society. As will be seen in this section, Hooke's theories about light, colours and inflection owe a considerable debt to his membership of the Society; his work builds on and, at times, celebrates the practical activity conducted by members of the organisation, particularly that carried out by his mentor Robert Boyle.

In the ninth chapter of *Micrographia*, after scrutinising a number of natural and artificial objects through his microscope, Hooke turns his attention to the mineral muscovite, or rather to the colours observable in it and other thin bodies, which he views as a phenomenon capable of challenging the account of colours contained in René Descartes's *Météores*[70]. Halfway through the chapter, he clearly felt the need to introduce a discussion about the nature of light, which he initiates with the comment: "it seems very manifest, that there is no luminous Body but has the parts of it in motion more or less"[71]. Before coming to the kind of motion that he is referring to, it is worth dwelling on the fact that he associates light with motion at all. Earlier in the work, in a chapter on small glass drops, he declares that liquid glass is less dense than solid, a claim that he supports with reference to the principle: "*Heat is a property of a body arising from the motion or agitation of its parts*"[72]. His subsequent association of light with motion, then, raises a problem, which will be familiar from the work on Francis Bacon in my first chapter: what is the relationship between light and heat?

[69] Sabra, *Theories of Light*, 187-95, and Shapiro, 'Kinematic Optics', 188-207.
[70] Hooke, *Micrographia*, H4^{r}-L2^{r}. For Descartes's account, see *Les Météores*, 330-2.
[71] Hooke, *Micrographia*, I3^{v}.
[72] *Ibid*. The chapter is G1^{r}-H2^{v}; the quote is from G3^{r}.

In the same year as *Micrographia*, Robert Boyle published a book about cold. In the preface, he explains his choice of subject-matter with reference to the importance of the study of heat, which he, like Hooke, describes as a kind of motion[73]. This description of heat comes with an unavoidable echo of Francis Bacon's provisional conclusions in book two of the *Novum organum*[74]. In fact, Bacon was almost certainly on Boyle's mind as he was preparing his book; the epigraph on his title-page is drawn from the aphorism that directly precedes the investigation into heat in the *Novum organum*: "Non fingendum, aut excogitandum, sed inveniendum, quid natura faciat, aut ferat" (Not to make up or invent what nature may do or allow, but to discover it)[75].

Hooke does not mention Boyle's work, but it seems likely that he was working with a similarly Baconian conception of heat. If so, his Baconian mindset may help to explain the urge to highlight differences between light and heat; after providing an overview of some of the substances that emit light, he observes: "though it be a motion, yet 'tis not every motion that produces it". He highlights some examples: "water and quick-silver, and most other liquors heated, shine not". On the other hand, he continues, "rotten Wood, rotten Fish, Sea water, Gloworms, *&c*. have nothing of tangible heat in them, and yet (where there is no stronger light to affect the Sensory) they shine some of them so Vividly, that one may take a shift to read by them"[76]. The idea that Hooke may have had a go at reading by the light emitted by rotten fish is a little distracting, but both the

[73] Boyle, *Touching Cold*, 208-24, at 208.
[74] For the investigation into heat, see Bacon, *Novum organum*, 218-72; for the conclusion that it is a kind of motion, see 262.
[75] The quote is drawn from Bacon, *Novum organum*, 214. It also appears on the title-page of the contemporary *Touching Colours*.
[76] Hooke, *Micrographia*, I4r.

emphasis on the difference between light and heat and the examples used to illustrate it are clearly reminiscent of the work of Bacon[77].

How does Hooke characterise the motion that he associates with light? Firstly, he writes, it must be "exceeding *quick*"; secondly, it must be "*Vibrative*"; and thirdly, it must be "*short*"[78]. As evidence for the first point, he refers to processes of "*fermentation* and putrefaction", presumably those undergone by shining fish and wood[79]. He substantiates the second and third points, however, with reference to the "shining of Diamonds", a spectacle that is described in greater detail on the preceding page: "a *Diamond* being rub'd, *struck*, or *heated* in the dark, shines for a pretty while after, so long as that motion, which is imparted by any of these Agents, remains"[80].

Experiments involving the rubbing and warming of a diamond were conducted at a meeting of the Royal Society on 21 October 1663, where one particularly interested party seems to have been Robert Boyle[81]. After carrying out some further trials on his own, he brought in a collection of observations, which was subsequently printed as an addendum to a work published in 1664, *Experiments and Considerations Touching Colours*[82]. The printed account is accompanied by a letter to Sir Robert Moray, in which he outlines the value of the subject-matter: "here we see Light produc'd in a dead and opacous Body, and that not as in rotten Wood, or in Fishes [...] by a Natural Corruption,

---

[77] For Bacon's use of these examples, see *Topica inquisitionis*, 244 and 246, and *Novum organum*, 226.
[78] Hooke, *Micrographia*, I4^{r-v}.
[79] *Ibid.*, I4^{r}.
[80] *Ibid.*, I3^{v}.
[81] Royal Society MS JBO/1, 237-40, at 240.
[82] For the minutes of the meeting held on 28 October 1663, see Royal Society MS JBO/1, 240-42, at 242. Boyle's descriptions were registered as 'Observations made 27th. October 1663 about M^{r} Clayton's Diamond' in MS RBO/2(i), 316-21. They were published under the same title in Boyle, *Touching Colours*, 197-201.

or by a Violent Destruction of the Texture of the Body"[83]. The attraction of the diamond, then, lies in its dissimilarity to traditional examples of luminescence; unlike the light produced by rotten wood or fish, the sparkling of the diamond does not depend on the decay or destruction of matter. Although Boyle allows himself this prefatory claim about the value of experimenting with the stone, he does his best to hold back from theorising; using Baconian terminology, he writes of his desire simply to provide "Luciferous [light-bearing] Experiments, by setting the Speculations of the Curious on work, in a diligent Inquiry after the Nature of Light"[84].

The speculations of the ever-curious Robert Hooke certainly seem to have been set to work, in particular when it comes to the short and vibrative character of light. The discussion in *Micrographia*, however, does not simply build on the practical work conducted at the Royal Society and described in print by Boyle; it also champions it. Hooke notes that the diamond was "first shewn to the *Royal Society* by Mr. *Clayton* a worthy member thereof". He continues: "Experiments made on which Stone, are since published in a Discourse of Colours, by the truly honourable Mr. Boyle"[85].

The idea that light involves a kind of quick, vibrative, short motion is commonly described as Hooke's 'wave' theory of light[86]. In *Micrographia*, the statement of the idea features as something of a way-station, with his principal focus being a theory of colours. He elaborates his thoughts on this front at some length, eventually setting out

---

[83] Boyle, 'A Copy of the Letter that Mr. Boyle wrote to Sir Robert Morray, to accompany the Observations touching the Shining Diamond', in *Touching Colours*, 187-96, at 188.
[84] *Ibid*., 188. For Bacon's conception of 'luciferous' experiments, see *Novum organum*, 156-8.
[85] Hooke, *Micrographia*, I3^v-I4^r.
[86] For an overview, see Sabra, *Theories of Light*, 187-95.

the conclusion that all colours derive from a mixture of blue and red, these being produced by the differing refractions of an oblique ‘pulse’ of light[87].

Hooke’s thoughts on light and colours appear, as mentioned, in a chapter on the mineral muscovite, which is listed in the table of contents at the end of the work under the title “Of Fantastical Colours”[88]. In the main body of the text, meanwhile, the following chapter is entitled “Of *Metalline*, and other real Colours”[89]. The distinction between ‘real’ and ‘fantastical’ colours in operation here can be clarified with reference to Robert Boyle’s book on colour, published the previous year. In his opening section, Boyle writes: “Colour may be considered, either as it is a quality residing in the body that is said to be coloured [...] or else as the Light it self, which so modifi’d, strikes upon the organ of sight, and so causes that Sensation which we call Colour”[90]. He acknowledges that the first conception is commonly thought of as ‘real’ colour, “especially in the Schools”. But he mounts a tentative defence of the use of the terms “True” or “Emphaticall” to describe the colour that is modified light[91].

Despite this brief attempt to rebrand ‘fantastical’ colour as ‘true’, the main body of Boyle’s book is dominated by the first conception, the traditional, scholastic idea of ‘real’ colour. The book contains numerous descriptions of experiments in which a substance has been induced to change colour, a theme that Boyle may have been inspired to pursue after he encountered work conducted by another Fellow of the Royal

[87] Hooke, *Micrographia*, K4^{r-v}, at K4^{v}. For an overview of his theory of colours, see Shapiro, ‘Kinematic Optics’, 188-207.
[88] Hooke, *Micrographia*, Kk4^{r}-Ll4^{r}, at Kk4^{v}.
[89] *Ibid.*, L2^{r}-M4^{r}.
[90] Boyle, *Touching Colours*, 25-60; the quote is from 29.
[91] *Ibid.*, 53-6; the quotes are from 53. He describes this conception of colour on 56 as “Probable”, although “it is but problematically Spoken”.

Society, Jonathan Goddard. The minutes of a meeting held on 7 May 1662 record the details of an experiment conducted by Boyle, in which two transparent liquids were seen to turn white when mixed[92]. The experiment may have been prompted by a paper that Goddard had read before members of the body in the January of the previous year, on the "mixture of severall liquors either having little, or no colour or being of different colours from those produced"[93].

The principal novelty of Hooke's work on colours lies in his dismissal of the distinction between 'real' and 'fantastic' colour. In the second of the two chapters in *Micrographia*, that on "*Metalline*, and other real Colours", he claims: "it seems an evident argument to me, that all colours whatsoever, whether in fluid or solid, whether in very transparent or seemingly *opacous*, have the same efficient cause". Unsurprisingly, this cause turns out to correspond to his previously expressed theory of colour: "some kind of *refraction* whereby the Rays that proceed from such bodies, have their pulse *obliquated* or confus'd in the manner I explicated in the former *Section*"[94]. On the following page, he explains his confidence: "By this *Hypothesis* there is no one experiment of colours that I have yet met with, but may be, I conceive, very rationably solv'd". He continues: "all the experiments about the changes and mixings of colours related in the Treatise of Colours, published by the *Incomparable* Mr. *Boyle*, and multitudes of others which I have observ'd do easily and naturally flow from those principles"[95]. Like his speculations about light, then, Hooke's thoughts about colour are founded on experiments, some of them published by Boyle, others observed, perhaps

[92] Royal Society MS JBO/1, 58
[93] The paper was read at a meeting on 16 January; see Royal Society MS JBO/1, 7-8, at 8. The quote is taken from the full title of 'A Brief Experimentall Accompt of y^{e} Production of some Colours', in MS RBO/1, 3-4.
[94] Hooke, *Micrographia*, L2^{v}.
[95] *Ibid*., L3^{r}.

at the Royal Society. Again, he not only builds on this practical work; he also celebrates it. In his reference to the experiments with the diamond, he refers to the 'truly honourable' Robert Boyle; here, the latter is 'incomparable'.

A later chapter in *Micrographia* is devoted to "a new Property in the *Air*, and several other transparent *Mediums*", a property that Hooke terms "*Inflection*"[96]. He opens the chapter with a list of curious phenomena, including the apparent disfiguration of the Sun and Moon near the horizon, a red tinge colouring bodies, and their appearance above the horizon when they are in fact below it[97]. His explanation for these phenomena involves a single concept: "nothing else, but a *multiplicate refraction*, caused by the unequal *density* of the constituent parts of the *medium*, whereby the motion, action or progress of the Ray of light is hindred from proceeding in a straight line, and *inflected* or *deflected* by a *curve*"[98]. In support of his theory, Hooke describes a number of experiments, providing illustrations of the instruments involved on the thirty-seventh plate of *Micrographia* (see figure 2). Unlike his comments on light and colour, here it is clear that he has carried out the work personally. As proof that air of different densities refracts light in different ways, for example, he describes heating the air in a small glass bubble and concludes: "you may find, if you place it [the bubble] in a convenient Instrument, that there will be a manifest difference, as to the refraction" (illustrated on plate 37, fig. 2)[99].

[96] *Ibid.*, Gg1^{r}-Ii4^{v}.
[97] *Ibid.*, Gg1^{r}-Gg2^{r}.
[98] *Ibid.*, Gg2^{v}.
[99] *Ibid.*, Gg3^{r}.

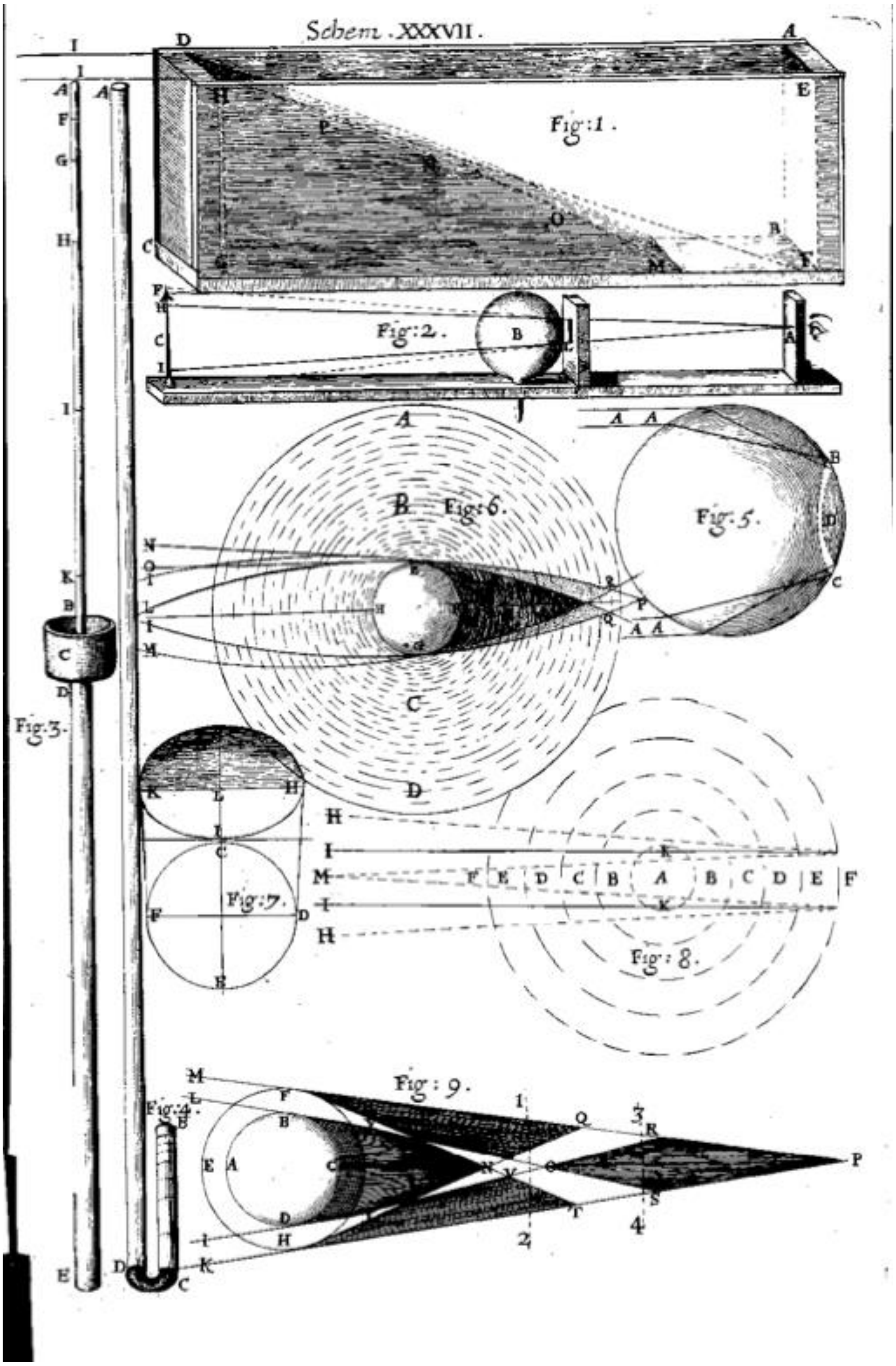


Fig. 2 Hooke, *Micrographia* (Wing H2620 – accessed via www.historicaltexts.jisc.ac.uk), plate 37, inserted between Gg2v and Gg3r.

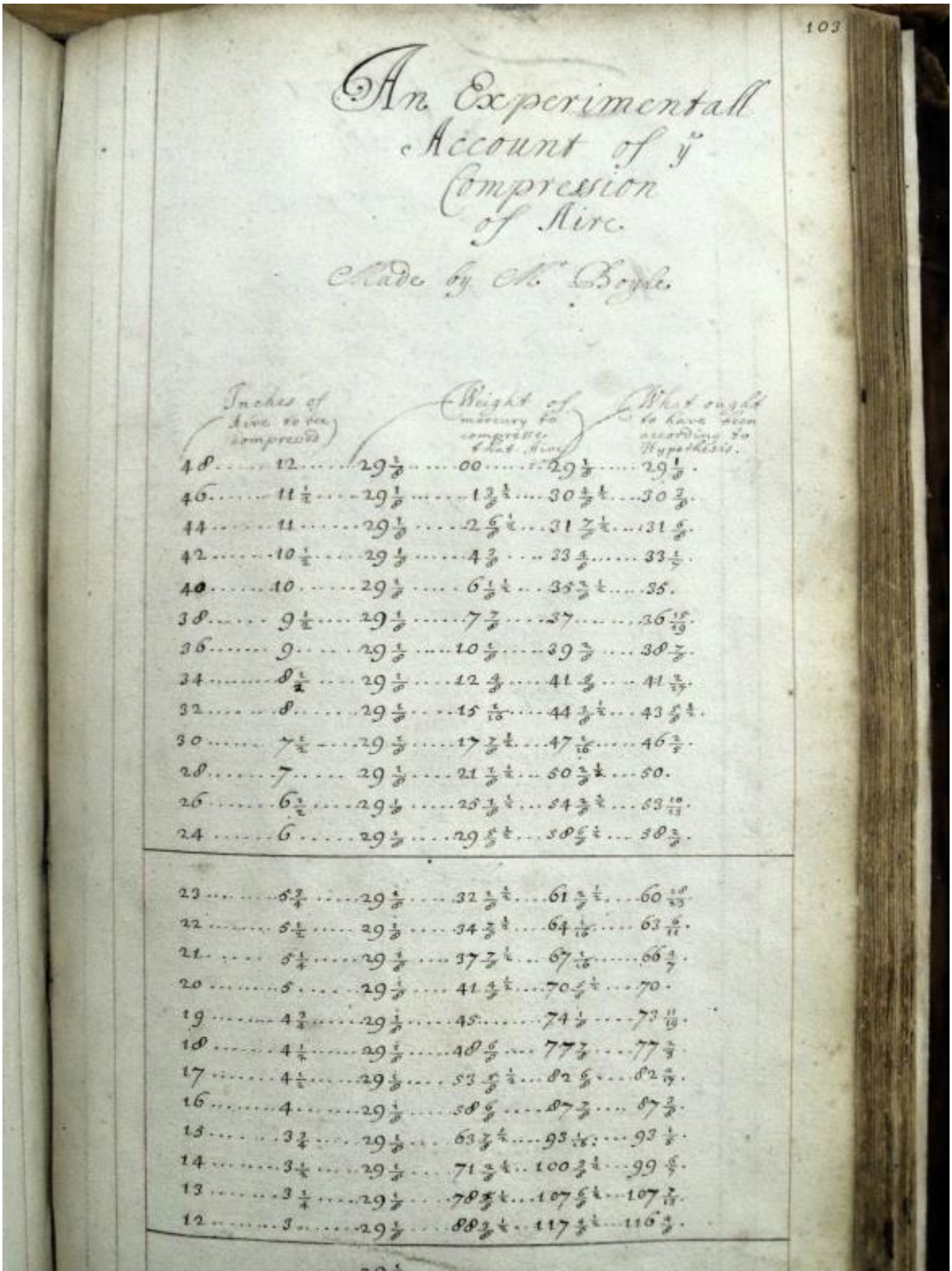
The idea that the air differs in density at different heights, Hooke continues, is clear from experiments trialling the Torricellian experiment at the top and bottom of mountains[100]. Not content with making the point, however, he goes on to describe two instruments that he has devised for exploring the relationship between density and pressure, a relationship governed by what is now known as 'Boyle's Law'[101]. One involves two glass cylinders, one inside the other, "for the finding by what degrees the Air passes from such a degree of Density to such a degree of Rarity". The other has a curved pipe "for the finding what pressure was requisite to make it pass from such a degree of Rarefaction to a determinate Density" (see plate 37, figs. 3 and 4)[102].

Long before he published details of these instruments, Hooke seems to have shared them with members of the Royal Society. At a meeting on 4 September 1661, Jonathan Goddard made an experiment with two cylinders of glass, one inside the other, "causing by five ounces of water, eight or ten ounces of quicksilver to rise 1 ¼ inch high"[103]. At the same session, William Croone produced an experiment involving the "Compression of Aire with Quicksilver in a crooked tube of glasse"[104]. On this occasion the device broke, but the following week Robert Boyle brought in a table of results made using a similar instrument, which was entered into the Register Book (see figure 3)[105]. Boyle then printed the table, alongside his statement of 'Boyle's Law', in a defence of his work with the air-pump, which he added to the second edition of the *Spring of the Air*,

[100] *Ibid.*, Gg3v.
[101] For the ascription of the law to Boyle, see Hunter, *Boyle: Between God and Science*, 134.
[102] Hooke, *Micrographia*, Gg3v.
[103] Royal Society MS JBO/1, 30-2, at 31.
[104] *Ibid.*, 32.
[105] 'An Experimentall Account of ye Compression of Aire', in Royal Society MS RBO/1, 103.

published in 1662[106]. An extended version of precisely the same table follows the description of the instrument in *Micrographia* (see figure 4)[107].

[106] For the table, see Boyle, *Defence of the Doctrine*, 62; for the statement of 'Boyle's Law', see 61.
[107] Hooke, *Micrographia*, Hh1^v.



103

An Experimentall Account of y^e Compression of Aire.

Made by M^r Boyle.

Inches of Aire to bee compressed			Weight of mercury to compresse that Aire		What ought to have been according to Hypothesis
48	12	29 1/8	00	29 1/8	29 1/8
46	11 1/2	29 1/8	1 3/8 1/2	30 4/8 1/2	30 3/8
44	11	29 1/8	2 6/8 1/2	31 7/8 1/2	31 6/8
42	10 1/2	29 1/8	4 3/8	33 4/8	33 1/7
40	10	29 1/8	6 1/8 1/2	35 2/8 1/2	35
38	9 1/2	29 1/8	7 7/8	37	36 15/19
36	9	29 1/8	10 1/8	39 2/8	38 7/8
34	8 1/2	29 1/8	12 4/8	41 5/8	41 2/17
32	8	29 1/8	15 1/16	44 1/8 1/2	43 5/8 1/2
30	7 1/2	29 1/8	17 7/8 1/2	47 1/16	46 3/5
28	7	29 1/8	21 1/8 1/2	50 2/8 1/2	50
26	6 1/2	29 1/8	25 1/8 1/2	54 2/8 1/2	53 10/13
24	6	29 1/8	29 5/8 1/2	58 6/8 1/2	58 2/8
23	5 3/4	29 1/8	32 1/8 1/2	61 2/8 1/2	60 18/23
22	5 1/2	29 1/8	34 7/8 1/2	64 1/16	63 6/11
21	5 1/4	29 1/8	37 7/8 1/2	67 1/16	66 4/7
20	5	29 1/8	41 4/8 1/2	70 5/8 1/2	70
19	4 3/4	29 1/8	45	74 1/8	73 11/19
18	4 1/2	29 1/8	48 6/8	77 7/8	77 2/3
17	4 1/4	29 1/8	53 5/8 1/2	82 6/8	82 4/17
16	4	29 1/8	58 6/8	87 7/8	87 3/8
15	3 3/4	29 1/8	63 7/8 1/2	93 1/16	93 1/5
14	3 1/2	29 1/8	71 2/8 1/2	100 3/8 1/2	99 6/7
13	3 1/4	29 1/8	78 5/8 1/2	107 6/8 1/2	107 7/13
12	3	29 1/8	88 3/8 1/2	117 4/8 1/2	116 4/8

29 1/8

Fig. 3 ‘An Experimentall Account of y^e Compression of Aire’, in Royal Society MS RBO/1, 103.

226 MICROGRAPHIA.

A Table of the Elaſtick power of the Air, both Experimentally and Hypothetically calculated, according to its various Dimenſions.

The dimenſions of the included Air.	The height of the *Mercurial Cylinder* counterpois'd by the *Atmoſphere.*	The *Mercurial Cylinder* added, or taken from the former.	The ſum or difference of theſe two *Cylinders.*	What they ought to be according to the *Hypotheſis.*
12	29 +	29 =	58	58
13	29 +	24 11/16 =	53 11/16	53 7/13
14	29 +	20 3/16 =	49 5/16	49 5/7
16	29 +	14 =	43	43 1/2
18	29 +	9 1/4 =	38 1/4	38 2/3
20	29 +	5 3/16 =	34 3/16	34 4/5
24	29	0 =	29	29
48	29—	14 1/2 =	14 1/2	14 1/2
96	29—	22 1/8 =	6 7/8	7 1/4
192	20—	25 5/8 =	3 3/8	3 5/8
384	29—	27 3/8 =	1 5/8	1 7/16
576	29—	27 7/8 =	1 1/8	1 5/24
768	29—	28 1/8 =	0 7/8	0 29/32
960	29—	28 3/8 =	0 5/8	0 29/40
1152	29—	28 7/16 =	0 9/16	0 10/16

Fig. 4 Hooke, *Micrographia*

(Wing H2620 – accessed via www.historicaltexts.jisc.ac.uk), Hh1[v].

Hooke's account of experiments made using these instruments allows him to suggest the likelihood "that there is a continual increase of rarity in the parts of the Air, the further they are removed from the surface of the Earth". The conclusion, of course, supports his theory that "the ray of Light passing obliquely through the Air […] will be continually, and infinitely inflected, or bended, from a straight, or direct motion"[108]. The experiments featured in *Micrographia*, then, support Hooke's theory of inflection. They do not, however, help with another question that seems to have been on his mind. Although he is confident that the density of the air decreases the further one moves from the surface of the earth, he laments the fact that "since we cannot yet find the *plus ultra*, beyond which the Air will not expand it self, we cannot determine the height of the Air"[109]. The prompt for his interest in this as yet unanswered question seems to have been the account of the problem included in Boyle's *Spring of the Air*[110]. Certainly, he does not pass up the opportunity to deploy some more laudatory language, referencing the "most accurate tryals", published in the "deservedly famous Pneumatick Book", by the "most illustrious and incomparable Mr. *Boyle*"[111].

As should now be clear, the text of *Micrographia* contains a considerable amount of theoretical musing about light, colours and inflection. Hooke would not, however, have been the man he was if he had not been aware of some of the practical applications of his theorising. After outlining his ideas about inflection, for example, he adds a list of queries, the first of which is: "Whether there may not be made an artificial transparent body of an exact Globular Figure that shall so inflect or refract all the Rays, that, coming

[108] *Ibid.*, Hh2^{v}.
[109] *Ibid.*, Hh2^{v}.
[110] Boyle, *Spring of the Air*, 261-4.
[111] Hooke, *Micrographia*, Hh2^{r}.

from one point, fall upon any *Hemisphere* of it; that every one of them may meet on the opposite side, and cross one another exactly in a point"[112].

In *La Dioptrique*, René Descartes had suggested that the best design for a telescope would make use of lenses featuring a hyperbolic curve, but glass-making technology of the period was not of the sophistication required to realise the idea[113]. In *Micrographia*, Hooke suggests that his theory of inflection may make it possible to side-step the problem: instead of working on the shape of the lens, he proposes working on the densities of its parts, so that "an exact Globular Figure" would, in fact, refract light like a lens of the Cartesian design. At this point, his prose becomes hyperbolic in another sense and it is worth quoting him at length:

> if so, there were to be hoped a perfection of *Dioptricks*, and a transmigration into heaven, even whilst we remain here upon earth in the flesh, and a descending or penetrating into the center and innermost recesses of the earth, and all earthly bodies […] this, could it be effected, would as farr surpass all other kinds of perspectives as the vast extent of Heaven does the small point of the Earth, which distance it would immediately remove, and unite them, as 'twere, into one, at least, that there should appear no more distance between them then the length of the Tube, into the ends of which these Glasses should be inserted[114]

[112] *Ibid.*, Ii1^{r}.
[113] For Descartes's suggestion, see *La Dioptrique*, 201-5. For an overview of the problem, see Burnett, *Descartes and the Hyperbolic Quest*.
[114] Hooke, *Micrographia*, Ii1^{r-v}.

His evident excitement about the practical application of his idea is communicated in a number of extraordinary phrases, among which it is particularly worth highlighting those in which he associates the "perfection of *Dioptricks*" with a "transmigration into heaven". The suggestion that a perfect lens would remove the distance between heaven and earth reads most obviously as a metaphor for the new visibility of tracts of space that improved telescopes would allow, but the comment is also reminiscent of the dramatic opening lines of the 'Preface' to *Micrographia*, in which optical instruments feature as tools for the partial reparation of the consequences of the Fall: "By the addition of such *artificial Instruments* and *methods*," he writes, "there may be, in some manner, a reparation made for the mischiefs, and imperfection, mankind has drawn upon it self, by negligence, and intemperance, and a wilful and superstitious deserting the Prescripts and Rules of Nature"[115].

When it comes to applying his notion of inflection to the construction of lenses, Hooke suggests, with some reservations, that a perfect lens could perhaps be built with "parcels of Glass of several densities", having "often observ'd in Optical Glasses a very great variety of the parts, which are commonly called Veins"[116]. Disappointingly, however, he interrupts himself: "of this enough at present, because I may say more of it when I set down my own Trials concerning the melioration of *Dioptricks*, where I shall enumerate with how many several substances I have made both *Microscopes*, and *Telescopes*, and by what and how many, ways"[117].

[115] *Ibid.*, $a1^r$-$g2^v$, at $a1^r$.
[116] *Ibid.*, $Ii1^v$.
[117] *Ibid.*, $Ii1^v$.

Hooke never provided a full account of the substances out of which he claims to have constructed optical instruments, although there is a slightly more revealing comment in the preface to *Micrographia*, the last part of the work to be printed[118]. Here, alongside other designs, he mentions microscopes made of "*Waters, Gums, Resins, Salts, Arsenick, Oyls,* and with divers other *mixtures* of *watery* and *oyly Liquors*"[119]. He does not make the link, but his claim to have built instruments using liquids may relate to his ideas about applying his theory of inflection. In the chapter at the end of the work he expressed doubts about glass; perhaps by the time he came to write the preface, mixtures of liquids seemed a more plausible way of proceeding.

If Hooke was thinking of building a liquid lens – and the subsequent publication of a design in the Royal Society's journal, *Philosophical Transactions*, strongly suggests that he was[120] – his work would have been facilitated by an instrument that could measure the refraction of light in liquids. It may not be a coincidence that a description of just such an instrument appears in the preface to *Micrographia*, only a few pages before the reference to microscopes made of "*watery* and *oyly Liquors*"[121]. By using this device, Hooke reports, he has found that "*Oyl of Turpentine* has a much greater Refraction then *Spirit of Wine*, though it be *lighter*; and that *Spirit of Wine* has a greater Refraction then *Water*, though it be lighter also"[122].

---

[118] For evidence that the preface was the last section to go through the press, see the letter from Hooke to Boyle, sent on 24 November 1664, in Hunter, Clericuzio and Principe, eds., *The Correspondence of Robert Boyle*, vol. 2, 411-3; he writes, 412, that the preface "has been stayed very long in the hands of some [members of the Royal Society], who were to read it".
[119] Hooke, *Micrographia*, f2ʳ.
[120] 'A Method, by which a Glass of a small Plano-convex Sphere may be made to refract the Rayes of light to a *Focus* of a far greater distance, than is usual', *Philosophical Transactions* 1, no. 10 (1666): Ee2ᵛ-Ee3ʳ. Issues are available at www.rstl.royalsocietypublishing.org; for an overview of the journal, see the website of the AHRC project 'Publishing the Philosophical Transactions': www.arts.st-andrews.ac.uk/philosophicaltransactions.
[121] Hooke, *Micrographia*, e2ᵛ-f1ʳ.
[122] *Ibid.*, f1ʳ.

Investigations into the refraction of light in various liquids were a prominent feature of Royal Society meetings held during the autumn of 1664. Hooke brought in his new device on 17 August, but it was not pressed into service until 29 September, when the body's secretary, Henry Oldenburg, reported a discovery recently made in Paris: light refracts more in ethanol ('spirit of wine') than it does in water, although the former weighs less[123]. The result was startling, but proved correct when members of the Society made use of Hooke's instrument at the following meeting[124]. Subsequent weeks saw a number of similar trials, featuring (among other substances) salt water, turpentine, sulphuric and nitric acid, solutions of potassium nitrate and potassium alum, and milk[125]. On 10 November, both Oldenburg and Hooke felt moved to report to Boyle the extraordinary finding of the previous day's gathering, that 'salad oil' (probably olive oil) refracted light to a greater degree than any liquid yet found[126].

When the results of some of these experiments appeared in the preface to Hooke's *Micrographia*, they were new and exciting discoveries. The idea of a liquid lens may be lurking somewhere behind his interest in the refraction of light in such diverse substances, but, if so, the connection is not made explicitly. In fact, Hooke's references to the refraction of light in turpentine and ethanol most obviously serve another purpose. They act out in miniature the role that I am ascribing to many of the

[123] For the meeting on 17 August, see Royal Society MS JBO/2, 120-2, at 120. For that on 29 September, see 131-4, at 133. I have not been able to identify the work in Paris mentioned by Oldenburg. For his place in the Royal Society, see Hall, *Henry Oldenburg*, 52-239.
[124] Royal Society MS JBO/2, 135-6, at 135.
[125] For details of these experiments, see the minutes of meetings held on 12 October, 2, 9, 16 and 23 November, and 7 December in Royal Society MS JBO/2, 136-8, 142-5, 145-9, 150-2, 153-6, and 158-61, at 137, 143, 147-8, 151-2, 154, and 159.
[126] Oldenburg to Boyle and Hooke to Boyle, in Hunter, Clericuzio and Principe, eds., *The Correspondence of Robert Boyle*, vol. 2, 394-8, and 398-400, at 395-6, and 398-9. For the description of the experiment, see Royal Society MS JBO/2, 145-9, at 147.

descriptions of practical work in the book. They celebrate the practical activity of the Royal Society, in this case in the face of competition from a rival group in Paris.

"*Light then is nothing else*": A Practical Defence

One careful early reader of Hooke's *Micrographia* was a young scholar in Cambridge, Isaac Newton[127]; the book very probably played a role in the decision, seven years later, to send his own thoughts on light to the Royal Society[128]. The thrust of this communication, sent on 6 February 1672 and subsequently published in the *Philosophical Transactions*, is that white light – far from being the pure, homogenous substance that it seems to be – is a composite of colours, an idea that Newton supports with what are now famous experiments with prisms[129]. The new theory was an obvious challenge to Hooke's understanding of colours, but the Royal Society's Curator of Experiments also seems to have latched onto the 'corpuscular' conception of light that he divined in Newton's account, a conception that he apparently interpreted as an attack on the 'wave' theory expressed in *Micrographia*.

Hooke's initial response to Newton's work is well known[130], but there has hitherto been no attempt to read the lectures on light that he delivered in the early 1680s, most likely as part of his ongoing tenure of the Cutler lectureship, within the same polemical context[131]. As will be seen, Hooke's lectures most obviously construct a defence of his wave theory of light, one that involves the mobilisation of practical work, much of which would have been familiar to his audience.

---

127 For Newton's notes on the work, see 'Out of M^r Hooks Micrographia'. For his time at Trinity College, Cambridge, see Westfall, *Never at Rest*, 66-104.
128 Letter 40, in Turnbull, Scott, Hall and Tilling, eds., *The Correspondence of Isaac Newton*, vol. 1, 92-107.
129 For an overview of his work, see Sabra, *Theories of Light*, 231-50.
130 See Sabra, *Theories of Light*, 251-64.
131 Hooke, 'Lectures on Light'. For his tenure of the Cutler lectureship, see Hunter, *Establishing the New Science*, 279-338.

Newton's treatise on light and colours was read at a meeting of the Royal Society on 8 February 1672. It was entered into the Register Book and assigned for examination to Seth Ward, Robert Boyle and Robert Hooke[132]. As far as we know, only Hooke completed the task; his critique was read on 15 February and sent to Newton, who replied promptly with the promise of a full response[133]. The effect of Hooke's analysis is to establish the older man as the master experimenter of the two. In the opening lines, he praises the "niceness and curiosity" of Newton's observations, which he can confirm, based on "many hundreds of tryalls". He continues, by reminding his audience that his own understanding of colours is based on "some hundreds of expts"[134]. These claims sound exaggerated, although with Hooke it is always difficult to be sure. The result, in any case, is to reinforce his practical credentials.

By praising Newton's results, Hooke places himself in a position to criticise the use of them. Not only, he suggests, is there nothing new in these observations; there is certainly not the decisive evidence, the 'experimentum crucis', that Newton thinks there is, "for the same phænomenon will be solved by my hypothesis, as well as by his, without any manner of difficulty or straining"[135]. Towards the end of the piece, he emphasises that he is not attacking the theory as a theory, "for I do […] esteem it very subtil and ingenious, and capable of solving all the phænomena of colours". His point

---

[132] Royal Society MS JBO/4, 230-2, at 230-1. For the copy in the Register Book, see 'A discourse of M^r^ Isaac Newton containing his New Theory about Light and Colours', in MS RBO/4, 138-47. For an overview of the life and career of Seth Ward, see Henry, 'Ward, Seth'.
[133] For the meeting on 15 February, see Royal Society MS JBO/4, 232-3. Hooke's critique is Letter 44, in Turnbull, Scott, Hall and Tilling, eds., *The Correspondence of Isaac Newton*, vol. 1, 110-6. For Newton's initial reply, see Letter 45, 116-7.
[134] Letter 44, in Turnbull, Scott, Hall and Tilling, eds., *The Correspondence of Isaac Newton*, vol. 1, 110.
[135] *Ibid*., 111. The phrase 'experimentum crucis' originates in Francis Bacon's discussion of the 'instantia crucis', one of the 'Instances with Special Powers', in the *Novum organum*, 318-38.

is simply: "I cannot think it to be the only hypothesis"[136]. The target, then, is neither Newton's experimental practice, nor his theoretical sophistication, but his understanding of the relationship between practice and theory.

Hooke bolstered his claims to be already aware of the experiments contained in Newton's treatise, by repeating some of them at meetings of the Royal Society on 24 April and 22 May[137]; the minutes for the later gathering, meanwhile, record his conclusion that "these Experimts. were not cogent to make light consist of different substances or divers powders as 'twere, but that those Phænomena might be explicated by motion of Bodyes propagated"[138]. Again, Hooke is attacking Newton's understanding of the relationship between theory and practice. As the somewhat sardonic reference to "divers powders as 'twere" makes clear, however, the target has shifted. Here, Hooke is taking aim not at Newton's explanation of the colours in a prism, but at the corpuscular conception of light that he saw lying behind it.

Newton took a long time to prepare and dispatch the response to Hooke's critique that he had promised back in February. Among the points featured in the long and careful letter that was read out at a meeting of the Society on 12 June is the insistence that his thoughts about colour do not depend on the corpuscular notion of light that he has advanced[139]. He is, however, much more concerned by the attempts to explain his

[136] Letter 44, in Turnbull, Scott, Hall and Tilling, eds., *The Correspondence of Isaac Newton*, vol. 1, 113.
[137] See the minutes for the meetings on 24 April and 22 May, Royal Society MS JBO/4, 246-7, and 252-3, at 247 and 252-3. For a description of these experiments, see 'An accompt of some Experiments about Refractions & Colors, made before the R.S. and described by Mr Hook', in MS RBO/4, 194-6, at 194 and 195. The experiments in question appear in the propositions that make up Newton's doctrine, 97-100, at 97 and 98.
[138] Royal Society MS JBO/4, 253.
[139] Letter 67, in Turnbull, Scott, Hall and Tilling, eds., *The Correspondence of Isaac Newton*, vol. 1, 171-93, at 173-4. For the minutes of the meeting, see Royal Society MS JBO/4, 254-5, at 255.

experimental results with prisms according to an alternative theory, which, he claims, are "not only *insufficient*, but in some respects unintelligible"[140]. He also responds, in similarly disparaging tones, to Hooke's dismissal of his 'experimentum crucis': "I cannot be convinced of its insufficiency by a bare denyall without assigning a reason for it". He continues: "I am apt to beleive, it hath been misunderstood"[141]. Now it is the understanding of the relationship between theory and practice displayed by the Royal Society's Curator of Experiments that is in question.

It is tempting to think that, when Hooke returned to light in the early 1680s, he would pick up where his debate with Newton had left off, especially as in late 1675 the latter had sent in some additional thoughts, which were discussed at the Royal Society and, as Hooke's diary reveals, at a secret meeting of a "New Philosophical Clubb" with which he was involved[142]. In fact, the dispute seems to have prompted a complete re-engagement with the subject. From the beginning of 1680, he devoted a series of lectures to light, published in seven sections after his death, in which he returned to first principles and constructed a case using the results of practical work, much of which would have been well known to members of the Royal Society[143].

[140] *Ibid.*, 176.
[141] *Ibid.*, 187.
[142] For Newton's communications, see 'M[r]. Isaac Newtons Observations mentioned in his Foregoing Hypothesis' and 'An Hypothesis explaining the Properties of Light'. The meeting of the philosophical club was held on 1 January 1676. Hooke writes: "We […] Resolvd upon Ingaging ourselves not to speak of any thing that was then revealed sub sigillo to any one nor to declare that we had such a meeting at all". He continues: "We began our first Discourse about light upon the occasion of Mr. Newtons Late Papers". See Robinson and Adams, eds., *The Diary of Robert Hooke*, 205-6.
[143] Hooke, 'Lectures on Light'. He may have felt emboldened by pleasant correspondence from Newton, sent in November and December 1679: see Letters 236 and 238 in Turnbull, ed., *The Correspondence of Isaac Newton*, vol. 2, 300-4, and 307-8. In the first letter, moreover, at 300-1, Newton claims that he has turned his back on philosophy.

The desire to build a case from the ground up may have been a factor in the number of Hooke's comments that deal with questions of methodology. The first set of lectures, for example, opens with the suggestion that what follows will involve the application of "mixt Geometry"[144]. The phrase seems to allude to the nature of the subject-matter: light is an aspect of the natural world that was traditionally handled geometrically[145]. But Hooke is, in fact, describing his investigative process; a couple of pages later, an overview of the thoughts of various ancient authors is interrupted with the comment: "as in pure Geometry nothing is to be let pass for a Truth, whose Cause and Principles are not clearly shown by the Progress of Reasoning, and the Process of Demonstration: So in Physicks Geometrically handled, nothing is to be taken for granted, nor any thing admitted for a true Conclusion, that is not plainly deduced from self-evident Principles"[146]. His approach, in other words, involves deductions from principles that he considers comparable to geometrical axioms[147].

Hooke follows his overview of ancient thought with a discussion of two of light's properties: its extensibility and speed[148]. He then introduces a third idea: light, he writes, is clearly the action of a body, rather than of a spirit, because it is accompanied by heat[149]. The association of light with heat is interesting, as it marks a departure from the Baconian emphasis, evident in *Micrographia*, on the difference between the two things. Hooke acknowledges that his idea is not uncontroversial: "To this many have

---

[144] Hooke, 'Lectures on Light', T2^{r}-Y2^{v}; the quote is from T2^{r}. An editorial header on T2^{r} suggests that the first section includes lectures "read about the beginning of 1680". Hooke refers to unspecified lectures in the entries of his diary for 29 January and 5 and 12 February; see Robinson and Adams, eds., *The Diary of Robert Hooke*, 437 and 438.
[145] For an overview of this approach, see Lindberg, *Theories of Vision*, 104-208.
[146] The overview of ancient thought is Hooke, 'Lectures on Light', T2^{v}-U2^{v}; the quote is on U1^{r}.
[147] For an overview of Hooke's thoughts on method, see Hesse, 'Hooke's Philosophical Algebra'. Michael Hunter has suggested that references to method in the Cutler lectures are the result of the pedagogical context; see *Establishing the New Science*, 303.
[148] Hooke, 'Lectures on Light', U2^{v}-X2^{r}.
[149] *Ibid.*, X2$^{r\text{-}v}$.

objected, that the Light of the Moon is so far from being actually hot, that it is actually cold, and the more those Rays are condensed the more is the Cold augmented". He has, however, an answer for such dissenters: "by divers Experiments purposely made, both by my self and divers others, we could not find that the Rays of the Light from the Moon had any such Power of Cold as is pretended"[150].

The mention of these experiments prompts thoughts of an investigation proposed by Francis Bacon in the *Novum organum*[151], but a more immediate source is Robert Boyle's work on cold of 1665. In a section containing "Promiscuous Experiments and Observations", Boyle reports that he has focussed the beams of the Moon, but without finding that "her light did produce any sensible degree, of cold or heat"[152]. Hooke does not directly reference Boyle's work, but he acknowledges that the experiments to which he is alluding do not support his ideas as much as he would perhaps have liked: they do not generate any tangible cold, but neither do they generate any tangible heat. He sidesteps the problem, by calculating that the light of the Moon is 104,368 times weaker than that of the Sun and "therefore 'tis no great Wonder, if a 104368th part of the heat of the Suns Rays is not felt by us"[153].

In the second set of lectures, read in Michaelmas term 1680, Hooke outlines his tripartite approach to the nature of light: firstly, he declares, he will examine the sources of light; secondly, the medium in which it is transmitted; and thirdly, the eye[154]. The

---

[150] *Ibid.*, X2v.
[151] See Bacon, *Novum organum*, 222.
[152] Boyle, *Touching Cold*, 418-458, at 421.
[153] Hooke, 'Lectures on Light', X2v-Y1r, at Y1r.
[154] The second set of lectures is Hooke, 'Lectures on Light', Y2r-Bb2r. They are dated to this time in an editorial header on Y2r. The tripartite approach appears on Z1r. In Hooke's diary he refers to lectures delivered on 4, 11, 18 and 25 November; see Robinson and Adams, eds., *The Diary of Robert Hooke*, 457 and 458.

remainder of the section is, accordingly, devoted to a lengthy account of the luminous body that he describes as the “greatest and most remarkable of all”, the Sun[155]. The next set of lectures, delivered in January and February of the following year, extends the discussion to the other heavenly bodies[156]. Hooke raises the suggestion that their luminosity, like that of the Sun, is the product of “an actual Fire, much of the same Nature with the Fires we here have burning upon the Earth”. He continues: “therefore if we find out what is the Nature of our Fire here with us, we may from that explain how it is generated and how it operates in the Heavens”[157].

Considerable discussion in Royal Society meetings held during the autumn of 1678 had been devoted to the nature of fire, perhaps inspired by observations on the subject in the *Spring of the Air* and *Micrographia*[158]. On 16 January 1679, Hooke showed that an apparently extinguished blaze could be re-ignited with the introduction of more air[159]. The following week, he conducted similar experiments and declared his theory: “that the Air was a Menstruum that dissolved all Sulphurous bodies by burning, and that without Air no such Dissolution would follow though the heat applied were as great”[160]. At a meeting held on 20 April 1681, he returned to the subject, possibly as a result of the thoughts on the nature of heavenly fire that he had included in his recent lectures. According to the Journal Book, he read a “Large Discourse”, followed by an “Experiment of Fire burning in a box”. No further details about the experiment are

[155] Hooke, ‘Lectures on Light’, Z1^{r}.
[156] *Ibid*., Bb2^{v}-Ee1^{v}; they are dated in an editorial header on Bb2^{v}.
[157] *Ibid*., Cc2^{v}.
[158] See the minutes for meetings on 31 October and 7, 14 and 21 November in Royal Society MS JBO/6, 127-9, 129-31, 131-3 and 133-6, at 129, 130-1, 132 and 134-5. For experiments involving combustion in the air-pump, see Boyle, *Spring of the Air*, 184-92. Hooke develops a theory of fire in *Micrographia* at P2^{v}-Q1^{v}.
[159] Royal Society MS JBO/6, 150-3, at 153.
[160] Royal Society MS JBO/6, 154-6, at 155-6; the quote is from 156. A similar expression of the idea appears in *Micrographia*, P4^{r}.

provided, but the minutes record that it was “pertinent for the Explanation of the Theory of Light debated in the above mentioned discourse”[161].

This meeting marks a change in the location in which Hooke’s thoughts about light were presented. It seems safe to assume that the posthumously published lectures correspond, in general, to material delivered before a general audience, with perhaps some Fellows in attendance, as part of his ongoing tenure of the Cutler lectureship[162]. The similarity, however, between the content of the third set of lectures and that in the discourse read before the Royal Society at the meeting on 20 April suggests that, at this point, he began using the same material in both forums. The pattern, moreover, continues. At the meeting held the following week, on 27 April, Hooke read another discourse, this time featuring “an Enumeration of all such bodies as afforded light and the manner how they would be made luminous”[163]. The substance of this discourse is almost certainly the same as that featured in the fourth set of lectures, dating to May 1681: having examined celestial luminosity, Hooke here moves onto terrestrial sources of light, drawing up an extensive list, in five categories[164].

The first and longest section of the list is devoted to fire[165]. The second contains observations of everyday things, such as metals, that, when heated, shine without burning[166]. The third is a curious choice: it is concerned with “all such Bodies as shine without Heat” and includes examples that are familiar from *Micrographia* and the work

---

[161] Royal Society MS JBO/7, 11.
[162] For a discussion of the audience of the Cutler lectures, see Hunter, *Establishing the New Science*, 293.
[163] Royal Society MS JBO/7, 12-3, at 12.
[164] Hooke, ‘Lectures on Light’, Ee2^{r}-Hh1^{v}; they are dated to May in an editorial header, Ee2^{r}. The list is on Ff1^{v}-Ff2^{v}.
[165] *Ibid.*, Ff1^{v}-Ff2^{r}.
[166] *Ibid.*, Ff2$^{r\text{-}v}$.

of Francis Bacon, including: “decaying Fish, as Whitings, Oysters, and many others, sometimes Flesh, as Veal”[167]. Although these phenomena are likely to have been extremely well-known to members of the Royal Society, they clearly remained of interest. The minutes of a meeting held earlier that year, on 23 February, record the observation that, when it comes to fishy substances, “the egs of a Lobster that had been boyled were asserted to shine the strongest”[168]. Meanwhile, back in March 1672, Robert Boyle had brought in a discourse describing a number of trials conducted on some shining meat; the copy in the Register Book reveals that the meat in question was a neck of veal, which had frightened one of his maids by glowing in the larder[169].

This section of Hooke’s list is curious, because it contradicts his previous assertion that all light is accompanied by heat. In the first set of lectures, delivered the previous year, he had insisted that moonlight comes with a certain degree of heat, albeit insensible, and continued: “The same Reason may be valid, why the Light of Gloworms, rotten Wood, Fish and the Late invented *Phosphorus,* do not at all affect the touch with their warmth”[170]. When it came to the list of substances included in the fourth set of lectures, he seems to have changed his mind; here, shining fish and meat are thought to emit light but not heat. Perhaps the desire to include familiar Baconian examples led him temporarily to reinforce the Baconian distinction between light and heat.

---

[167] *Ibid.*, Ff2^{v}. For Bacon’s comments about rotten fish, see *De augmentis scientiarum*, 612, and *Topica inquisitionis*, 244.
[168] Royal Society MS JBO/6, 272-3, at 272.
[169] See the minutes for the meeting held on 21 March, Royal Society MS JBO/4, 240, and ‘Some Observations about Shining Flesh’, in MS RBO/4, 130-7, at 130.
[170] Hooke, ‘Lectures on Light’, Y1^{r}.

The fourth section of Hooke's list features items that "shine by the Impression of Light made upon them, by being exposed only to the Light of the Sun or the Day"[171]. The reference is to phosphorescent substances, a subject of some fascination for early Society members[172]. Most recently, on 16 February 1681, the diplomat Robert Southwell had brought in a white powder made of *lapis smaragdinus*, which, when heated on a copper plate, would "shine like a glow worme"[173]. The previous year, Robert Boyle had published a book on phosphorescence, the *Aerial Noctiluca*; in his dedication to the clergyman John Beale, he distinguished between what he referred to as 'artificial' phosphoruses, the subject of the book, and "*Those* that may be stil'd Natural, as Glow-worms, some sorts of rotten Wood and Fishes, and a few others"[174].

The final section in Hooke's list encompasses things that shine by motion and includes examples that would also have been extremely familiar to members of the Royal Society. He refers, for example, to diamonds, no doubt an allusion to the stone brought into the Society in 1663 by John Clayton and investigated by Robert Boyle[175]. He also mentions "clean warmed Linnen, as has been lately experimented by Dr. *Crone*"[176]. The comment is another reference to business conducted at the meeting on 23 February 1681, which, alongside a discussion of shining fishy substances, included a description by William Croone of nocturnal experimentation that involved "the shining of a cleane shift when putt on very warme and rubbed with his hand"[177].

---

[171] *Ibid.*, Ff2^{v}.
[172] For an overview, see Golinski, 'A Noble Spectacle'.
[173] Royal Society MS JBO/6, 270-2, at 272. For an overview of his life and career, see Barnard, 'Southwell, Sir Robert'.
[174] Boyle, *The Aerial Noctiluca*, 269-76, at 269. For an overview of Beale's life and career, see Woodland, 'Beale, John'.
[175] Hooke, 'Lectures on Light', Ff2^{v}.
[176] *Ibid.*, Ff2^{v}.
[177] Royal Society MS JBO/6, 272-3, at 272.

Like his discussion of celestial bodies, then, Hooke's list of terrestrial sources of light draws on a considerable amount of practical work, much of which was well known to members of the Royal Society. If I have discussed the items included in this list in some detail, it is because they are followed immediately by the re-iteration of his theory of light: "*Light then is nothing else but a peculiar Motion of the parts of the Luminous Body, which does affect a fluid Body that incompasses the Luminous Body, which is perfectly fluid, and perfectly Dense, so as not to admit of any farther Condensation; but that the Parts next the Luminous Body, being moved, the whole Expansion of the that fluid is moved likewise*"[178]. The difference between this comment and the earlier expression of the theory in *Micrographia* is minimal. In fact, Hooke's return to light seems simply to have confirmed the idea that he had held all along.

It is tempting to think that the statement of Hooke's theory is more solid this time around, due to his laborious accumulation of data, but he is curiously evasive about the relationship between his conclusion and the practical work on which it is based: "It would be too long", he claims, "here to recount to you the whole process of the Examination of these Evidences [...] It will suffice at this time to tell you the Result and Conclusion"[179]. In the light of this reluctance to outline the process by which he arrived at his conclusion, Hooke's accumulation of material looks more obviously like a polemical exercise than an intellectual one. He brought together a weight of evidence, much of it drawn from hands-on activity that members of his audience would have recognised. The effect is considerable and, at first sight, compelling.

[178] Hooke, 'Lectures on Light', Gg1^{r}.
[179] *Ibid.*, Gg1^{r}.

Three further sections are included in the collection of posthumously published lectures. The fifth is devoted to the eye and the sixth deals with questions regarding the propagation of light[180]. The final section seems to have little relationship with what precedes it. The early editor of the lectures Richard Waller comments: “our Author […] leaves this Subject, I must confess, in some sense imperfect”; as he notes, Hooke turns his attention to “the following Discourse wherein [he] attempts to shew how we come by the Notion of Time”[181]. Waller had the impression that the lectures are incomplete, but in one sense the job was done: with his compendious collection of practical information, Hooke had mounted a convincing defence of his theory of light.

***

It is worth reflecting on the locations that witnessed Hooke’s engagement with what he perceived as an attack on his wave theory. After being sent to the Royal Society, Newton’s treatise on light and colours was published in the organisation’s journal, the *Philosophical Transactions*. But Hooke’s principal response was delivered at the body’s weekly meetings. He did not simply draw on practical work that had been carried out at the Society; he also made his defence in this arena. There is little obvious reason for such reticence. From an intellectual standpoint, the advancement of knowledge would surely have benefited from an open debate. From a polemical one, if he was making a convincing case, the more people that knew it the better. He had not

[180] Section five is Hooke, ‘Lectures on Light’, Hh2^{r}-Kk2^{v}; it contains material similar to that discussed by Hooke at a Royal Society meeting on 8 June 1681; see Royal Society MS JBO/7, 20-1, at 21. Section six is ‘Lectures on Light’, Ll1^{r}-Nn1^{r}; it provided the content for a discourse read before the Society at a meeting on 3 May 1682; see MS JBO/7, 77-9, at 77-8. A continuation was read on 17 May; see 80-1, at 81.

[181] The section is Hooke, ‘Lectures on Light’, Nn1^{v}-Pp2^{v}; Waller’s comment is on Nn1^{v}. The section is undated, but it corresponds to a discourse delivered at a gathering of the Society on 21 June 1682; see Royal Society MS JBO/7, 89-90, at 90. For the life and career of Richard Waller, see Mulligan, ‘Waller, Richard’.

been afraid of publishing his theory of light in *Micrographia* in 1665. If the theory remained correct, as he was claiming, there was no reason not to defend it in print in 1681.

Perhaps, when it comes to the defence of his wave theory, Hooke's choices say something about his relationship with the Royal Society. He had, after all, laboured to leverage his practical abilities and secure for himself a prominent position in the organisation. He had published a successful book, which had both exemplified and championed the practical approach of the body. When it came to defending his theory of light, his goal seems to have been to convince neither Newton, nor a broader public, but the select group of men whose respect he thought he had earned.

Isaac Newton Waits for Robert Hooke to Die

In the popular imagination, Isaac Newton (1643-1727) is a somewhat forbidding figure: for many people, the image of a secretive, moody man stands as the epitome of what it means to be a scientific genius. Of course, ever since John Maynard Keynes's famous declaration, in an essay published in 1947, that he was "not the first of the age of reason", but "the last of the magicians", historians have become accustomed to challenging the idea that his genius was simply or solely 'scientific'[1]. Betty Jo Teeter Dobbs has published two classic studies of Newton's alchemy[2], an area of his activity that has since been investigated by Karin Figala and William Newman[3]. Newton's religious thought is the subject of a book by Frank Manuel and of two volumes of essays edited by James Force and Richard Popkin[4]. More recently, Jed Buchwald and Mordechai Feingold have detailed his work on chronology[5]. Scholars working in these and other areas of Newton's intellectual life have been aided by the vast range of material now available online as part of *The Newton Project*[6].

If the image of Newton the man of science became more complicated over the second half of the twentieth century, however, the image of Newton the genius has only recently come under real scrutiny, with the publication in 2002 of Patricia Fara's examination of its construction in the century following Newton's death[7]. It seems safe to say that Newton still possesses something of an aura, the product of generations of

[1] Keynes, 'Newton, the Man', 27.
[2] Dobbs, *The Foundations of Newton's Alchemy*, and *The Janus Faces of Genius*.
[3] Figala, 'Newton's Alchemy', and Newman, ed., *The Chymistry of Isaac Newton*.
[4] Manuel, *The Religion of Isaac Newton*; Force and Popkin, eds., *Essays on the Context, Nature and Influences of Isaac Newton's Theology* and *Newton and Religion*.
[5] Buchwald and Feingold, *Newton and the Origin of Civilization*.
[6] Iliffe and Mandelbrote, eds., *The Newton Project*.
[7] Fara, *The Making of Genius*.

hagiography. In 2001, in a tribute to the best of his many biographers, Richard Westfall, I. Bernard Cohen asked who else would have been able to cover the range of Newton's activity[8]. The praise is not undeserved: Westfall's biography, published in 1980, is admirably broad in its scope. And yet, it contains phrases that say more about modern notions of genius than they do about the life and times of a seventeenth-century philosopher: "Genius of Newton's order", he writes, for example, "does not readily find companionship in any society in any age"[9].

There remains, then, a place for work that seeks to situate Newton's supposed genius in the context of contemporary natural philosophical activity, most obviously the work conducted at the Royal Society, and particularly that performed by the Society's Curator of Experiments, Robert Hooke[10]. Newton's long-standing enmity towards Hooke is a well-known feature of his intellectual career, one that has sometimes been attributed to a clash of personalities between the two men: in his biography of Newton, for example, Richard Westfall describes Hooke as "more plausible than brilliant. He had ideas on every subject and was ready to put them into print without much hesitation". Newton, by contrast, "was obsessed with the idea of rigour and could hardly convince himself that anything was ready for publication"[11]. There may be something to this depiction, but my approach in what follows is characterised by the idea that the conflict was first and foremost a struggle for status: at issue, to my mind, was the question of who was England's leading optical philosopher[12].

---

[8] Cohen, 'Some Recollections', 318.
[9] Westfall, *Never at Rest*, 76.
[10] For work along these lines, see Bechler, 'Newton's Disputes'; Ben-Chaim, *Experimental Philosophy*, 72-99; Johns, 'Reading and Experiment', 257-63; Mamiani, 'The Structure of a Scientific Controversy'; and Schaffer, 'Glass Works'.
[11] Westfall, *Never at Rest*, 243. Similar comments appear in Brewster, *Memoirs*, vol. 1, 86-7, and Manuel, *A Portrait of Isaac Newton*, 138-9.
[12] Alan Shapiro also expresses this idea in 'Twenty-Nine Years in the Making', 418-21.

The first section of the chapter focuses on Newton’s invention of the reflecting telescope, an instrument that may, in part, owe its existence to his encounter with work on similar devices conducted by the Royal Society. The second examines his investigation into what are now known as ‘Newton’s Rings’ and raises the suggestion that his work may have been the product of a desire to counter Hooke’s negative assessment of his theory about the heterogeneous nature of light. Finally, the third describes his ultimately unsuccessful attempts to explain the phenomenon of diffraction, which, I suggest, may also have been prompted by Hooke’s objections to his theory of light. The goal is not to diminish Newton’s achievements, but to set them in the context of contemporary natural philosophical activity and, in particular, in a polemical context: his conflict with Robert Hooke. It is, however, a process of contextualisation that involves avoiding any reference to him as a ‘genius’.

“M^{r}. Newton’s new Telescope was examined and applauded”: The Reflecting Telescope and the Royal Society

The celebrity of Isaac Newton’s work in optics rests principally on what was at the time a radical idea: that white light is heterogeneous, a composite of colours, rather than the pure substance that it seems to be[13]. He is, however, also famous for the invention of an optical instrument: the reflecting telescope. The idea of a device that would focus light by reflecting it with a concave mirror, rather than refracting it through a lens, had been circulating for some time. The French natural philosopher Marin Mersenne had included a design in the preface to his *Harmonicum libri* of 1636, as, more recently, had the Scottish mathematician James Gregory in his *Optica promota*, published in 1663[14]. Newton’s design was subtly different to Mersenne’s and Gregory’s, but his achievement was fundamentally a practical one: his reflecting telescope is generally acknowledged to be the first to have been successfully built[15].

Newton’s telescope was received and examined by the Royal Society in London in 1672. In accounts of the invention, however, the body has generally been painted in a rather passive light, its role limited to soliciting the new telescope from the Cambridge man and ensuring that he received the credit for it[16]. As I will highlight, however, there is some evidence that Newton may have been galvanised by an encounter with the work on optical instruments that Society members were conducting at this time. Indeed, his

---

[13] For an overview of Newton’s work on light, see Sabra, *Theories of Light*, 231-50.
[14] Mersenne, *Harmonicorum libri*, aiii^{r}-cii^{v}, at aiii^{v}; Gregory, *Optica promota*, N2^{v}-N4^{r}.
[15] For the early development of the reflecting telescope see Asimov, *Eyes on the Universe*, 58-68, and King, *The History of the Telescope* 48-9.
[16] See, for example, Asimov, *Eyes on the Universe*, 63-4, and King, *The History of the Telescope*, 68-77, as well as Hall and Simpson, ‘An Account’, Mills and Turvey, ‘Newton’s Telescope’, and the account in Westfall, *Never at Rest*, 232-7.

awareness of their activity may have shaped the way in which he presented his device when he sent it to London. The development of the reflecting telescope is certainly the product of one man's talent; that talent, however, belongs in the context of a thriving natural philosophical culture.

Isaac Newton was elected a Fellow of the Royal Society at a meeting on 11 January 1672, at which attendees were brought up to speed on events occurring over the Christmas period: Newton had sent a reflecting telescope to London, which had been examined by the Society's President, Viscount Brouncker, by prominent members Sir Robert Moray, Sir Paul Neile, and Christopher Wren, by the Curator of Experiments, Robert Hooke, and by the King himself, at Whitehall[17]. The instrument in question was brought in to the meeting of the following week; the minutes in the Journal Book record that "M^r^. Newton's new Telescope was examined and applauded"[18].

On 2 January, the Society's secretary, Henry Oldenburg, had written to Newton, describing the admiration at Whitehall and proposing that a description of the new telescope be sent to Paris, to the Dutch natural philosopher Christiaan Huygens, in order to avoid any future priority disputes[19]. In his response, Newton declares that he is "surprised to see so much care taken about securing an invention to mee, of wch I have hitherto had so little value", a statement of modesty that it is tempting to take at face

---

[17] Royal Society MS JBO/4, 223-5, at 223. For overviews of the lives and careers of Brouncker and Neile, see McIntyre, 'Brouncker, William', and Simpson, 'Neile, Sir Paul'. For Sir Robert Moray, see David Stevenson's introduction to *Letters of Sir Robert Moray*. For Christopher Wren, see Lisa Jardine's biography, *On a Grander Scale*. For Hooke, see Inwood, *The Man Who Knew Too Much*, and Jardine, *The Curious Life*. Newton had been nominated for membership at the previous meeting, on 21 December; see MS JBO/4, 222.
[18] Royal Society MS JBO/ 4, 225-6, at 226.
[19] Letter 29, in Turnbull, Scott, Hall and Tilling, eds., *The Correspondence of Isaac Newton*, vol. 1, 73-4. For an overview of Oldenburg's place in the Royal Society, see Hall, *Henry Oldenburg*, 52-239. For Huygens's relationship with the body, see Hall, 'Huygens's Scientific Contacts with England'.

value; it certainly chimes with the modern image of a reclusive genius. It is, however, worth noting that his apparent disinterest also serves to push back the date of his breakthrough: "had not the communication of it been desired, [I] might have let it still remained in private as it hath already done some yeares"[20].

Five years earlier, in the spring of 1667, members of the Royal Society had witnessed a leap forward in the making of optical instruments that is comparable to Newton's. At a meeting on 21 March, Sir Paul Neile informed those present: "one M[r]. Smethwick had shewed a Glasse, which he affirmed to be of a Conick Section". The minutes include Sir Paul's description of testing the lens in a telescope: "they saw a Tree very well on Shooter's hill, without any considerable colours"[21]. The news was striking. One difficulty facing the users of seventeenth-century lenses was the appearance of colours. The problem is now known as 'chromatic aberration', but at the time it was attributed to the failure of spherical lenses to focus light to a point (now referred to as 'spherical aberration'). In *La Dioptrique*, published in 1637, René Descartes had recommended a design featuring a hyperbolic curve (one of the conic sections), but all attempts to construct lenses of this kind had proved disastrous[22].

Francis Smethwick's achievement, then, was dramatic and he was immediately elected a Fellow of the Society[23]. He is an intriguing character: at present, I can turn up few

[20] Letter 33, dated 6 January, in Turnbull, Scott, Hall and Tilling, eds., *The Correspondence of Isaac Newton*, vol. 1, 79-81, at 79.
[21] Royal Society MS JBO/ 3, 74-5. Shooter's Hill is in Greenwich.
[22] Descartes, *La Dioptrique*, 201-5. For an overview of the problem, see Burnett, *Descartes and the Hyperbolic Quest*. For the contemporary attribution of colours to spherical aberration, see 17. Smethwick appears briefly on 92n.
[23] He was proposed on 28 March by John Wilkins and elected the following week; see Royal Society MS JBO/3, 79-82 and 82-4, at 79 and 82.

relevant details about his life and career[24]. And yet, at a meeting held in February 1668 he brought in a telescope, microscope and two burning glasses, all apparently featuring non-spherical lenses[25]. In a letter to Robert Boyle of 3 March, Henry Oldenburg reported that the telescope was four feet long, contained three of the new lenses, and performed much better than an instrument of the traditional design: "by magnifying the objects more, and representing ym more exactly in their due proportions, without colors"[26]. The Royal Society examined the instruments again on 5 and 12 March[27]. In another letter to Boyle, sent before the second meeting, Oldenburg writes that the body was already pretty satisfied, firstly, that the lenses were non-spherical and, secondly, that they far out-performed spherical ones. But, he continues: "we cannot be too rigid in ye examen, before we give a publick testimony of it to the world"[28]. The lenses evidently withstood the scrutiny, as shortly afterwards an account of their performance was published in the *Philosophical Transactions*[29]. On the face of it, Francis Smethwick had achieved something extraordinary.

Smethwick has, however, no great place in the history of science. Despite replicating his successes in June 1671 in a telescope six and a half inches long and in December 1673 in a microscope, his name is almost totally unknown[30]. One reason may be the fact that he was not as open with the Royal Society as he could have been. In his first

---

[24] Michael Hunter records that he was a pupil of William Oughtred and the library-keeper at Westminster; see 'Appendix 3: Biographical Information about Fellows', in *The Royal Society and its Fellows*, 72-7, at 73.
[25] The meeting was on 27 February; see Royal Society MS JBO/3, 180-5, at 181.
[26] Letter 804, in Hall and Hall, eds., *The Correspondence of Henry Oldenburg*, vol. 4, 223-6. For the description of the instruments, see 223-4; the quote is from 223.
[27] Royal Society MS JBO/3, 186-7 and 187-9, at 186-7 and 187.
[28] Letter 808, dated 10 March, in Hall and Hall, eds., *The Correspondence of Henry Oldenburg*, vol. 4, 234-6, at 235.
[29] 'An Account of the Invention of Grinding *Optick* and *Burning*-Glasses, of a Figure not-*Spherical*, produced before the *Royal Society*'. *Philosophical Transactions* 3, no. 33 (1668): Xxx2^{r-v}.
[30] He brought the instruments into meetings on 22 June 1671 and 4 December 1673; see Royal Society MS JBO/3, 199-200, at 200, and MS JBO/5, 50-1.

letter to Boyle about the lenses, Oldenburg writes that the inventor "maintains, they are of a figure not-Spherical". But, he continues: "whether Ellipticall or Hyperbolicall, he declares not"[31]. Given his reticence on this point, it looks unlikely that Smethwick ever shared the secret at the heart of the breakthrough: his method for grinding lenses. Indeed, if he had, Christopher Wren and Robert Hooke would presumably not have invested so much energy in the area, all of it in vain, from the summer of 1669 to the spring of 1671[32]. If he had managed to crack the art of constructing non-spherical lenses, Francis Smethwick seems to have kept it to himself.

At about the same time, the Royal Society was the location for another great leap forward in optical instrumentation, this time a more substantiated one. Robert Hooke had first mentioned some thoughts about the improvement of telescopes in the autumn of 1666[33]. On 28 February of the following year, he produced "a Box with Optick glasses fitted in it, designed to contract the power of a long Telescope into a short one"[34]. This description, taken from the Journal Book, makes the instrument sound a little like a reflecting telescope, but in fact it probably functioned in the same way as a device depicted in Hooke's small volume of 1676, *A Description of Helioscopes*. In this book, he describes a shortened telescope, which reflects light with plane mirrors, before focusing it in the conventional way, by means of a lens[35].

[31] Letter 804, in Hall and Hall, eds., *The Correspondence of Henry Oldenburg*, vol. 4, 223.
[32] For descriptions of Wren and Hooke's designs for lens-grinding instruments, see the minutes of meetings held on 10 and 17 June 1669, Royal Society MS JBO/4, 63-5 and 65-8, at 64 and 65-6. On 20 January 1670, Hooke reported that Wren's design was not practicable; see 108-9. He brought in a prototype of his own design on 12 January the following year, which was ordered to be tested; see 165. If the test was carried out, there is no record that the results were reported to the Society.
[33] See the minutes of meetings on 28 November and 5 December, Royal Society MS JBO/3, 42-4 and 47-8, at 44 and 48.
[34] Royal Society MS JBO/3, 67-9, at 68.
[35] Hooke, *A Description of Helioscopes*, B2^{v}.

Three weeks later, Hooke was urged to test his new two-foot telescope against a six-foot one of the traditional design[36]. After a number of reminders, he finally brought in the two instruments on 16 May[37]. The delay perhaps betrays a sense of wariness about how his device would perform. If so, he was right to be concerned; the minutes for the meeting report: “Being compared by exchanging the Glasses. the Company judged the common one, to shew the object more clear, than the other did; though both shewed the Object of near the same bignesse”. The results, in other words, are mixed: the new instrument has an impressive power of magnification, equal to a telescope three times as long, but the blurriness of the image undermines its value.

One of Hooke’s problems was ensuring that the mirrors in the device were perfectly smooth and polished. The point was raised by Society members when he first produced the telescope on 28 February[38]. The following week he announced that he had hit on an appropriate metallic substance, which he intended to grind with sand and polish with putty[39]. His ideas, however, clearly did not work out as well as he had hoped: one of the defects identified on 16 May was the fact that the mirrors were not as smooth as they could be[40]. Ever optimistic, Hooke declared that that this and other problems with the device could easily be remedied, but, despite being reminded at subsequent meetings, he never produced an updated version[41].

[36] Royal Society MS JBO/3, 74-9 (no 76-7), at 74.
[37] Royal Society MS JBO/3, 95. He was reminded on 28 March, 11 April, 25 April, and 9 May; see 79-82, 84-7, 89-92, 93-5, at 82, 87, 92, 94.
[38] Royal Society MS JBO/3, 67-9, at 68.
[39] Royal Society MS JBO/3, 69-71, at 70.
[40] Royal Society MS JBO/3, 95-7, at 95.
[41] He was reminded on 30 May and 6 June; see Royal Society MS JBO/3, 99-101 and 102-4, at 101 and 104.

Speaking generally, Isaac Newton could have been aware of this and other Royal Society activity, perhaps via Isaac Barrow, a Fellow of Trinity College, Cambridge, and a member of the Society since 1662, although he did not attend many meetings[42]. Newton and Barrow were certainly familiar by 1669, when the latter's lectures on optics were published (Newton is thanked in the prefatory materials), and it seems likely that the acquaintance dates to 1667, when the lectures were first delivered[43].

A particularly suggestive coincidence, however, lies in the fact that John Pearson, the Master of Trinity, was elected as a Fellow of the Society on 14 March 1667, one week before the meeting at which Sir Paul Neile informed the company of Francis Smethwick's new lenses and Robert Hooke was encouraged to compare his two-foot telescope against a standard six-footer[44]. It seems safe to say that Pearson was probably not as philosophically literate as some of the regular attendees of Royal Society meetings[45]. But, if he was still in town, it is certainly possible that he attended the session following his election and, conscious of Barrow and/or Newton's interest in some of the subjects under discussion, provided a relation of the week's business.

The young natural philosopher had, of course, already turned his attention to optical matters[46]. Observations and experiments regarding light, colours, and vision appear in

---

[42] He was elected on 17 September; see Royal Society MS JBO/1, 83-5, at 85. For an overview of his life and career, see Feingold, 'Isaac Barrow'.
[43] The lectures were published as *Lectiones XVIII*. Newton is thanked in the 'Epistola ad lectorem', [*]1^r-v, at [*]1^r. For a discussion of the lectures, their publication, and Newton's involvement, see Shapiro, 'The *Optical Lectures*', 105-13.
[44] Royal Society JBO/3, 71-4, at 71.
[45] For an overview of his interests, which are more ecclesiastical than natural philosophical, see de Quehen, 'Pearson, John'.
[46] For the development of Newton's work in optics up to 1670, see Alan Shapiro's introduction to the *Optical Lectures*, 10-15.

a manuscript treatise, 'Certain Philosophical Questions', which dates to 1664-5[47]; a more focussed investigation, 'Of Colours', followed in 1665-6[48]; meanwhile, fragmentary notes from these years betray an interest in reflection and refraction[49]. None of these pieces, however, makes any mention of telescopes and it is worth considering the idea that Newton's work in the area was stimulated by an encounter with the work of the Royal Society, perhaps the result of John Pearson's election.

There is certainly evidence that Newton first engaged seriously with the Royal Society in the spring of 1667. A table of accounts in a manuscript known as the 'Fitzwilliam Notebook' records the purchase of Thomas Sprat's *History of the Royal Society*, published that year[50]. At the same time Newton spent nine shillings sixpence on what is referred to as "Philosophicall Intelligences"[51], presumably a reference to a bulk buy of back issues of the *Philosophical Transactions*, given that another manuscript features his detailed notes on the first 24 issues of the journal[52]. If, at this point, he bought all the issues published thus far, his acquisition took place at some point after 8 April and before 6 May: not long, in other words, after Pearson's time in London[53].

Newton's accounts for the year also reveal the purchase of a lathe and table, as well as drills, chisels, a whetstone, a hammer, and a mandrel[54]. The most obvious use of such

47 Newton, 'Certain Philosophical Questions'. For a discussion of the comments on optical matters, see J.E. McGuire and Martin Tamny's commentary, 241-74.
48 Newton, 'Of Colours'. For the piece's relationship with the 'Certain Philosophical Questions', see McGuire and Tamny's commentary, 262-72.
49 Newton, 'Early Notes on Reflection and Refraction' and 'The Refraction of Light at a Spherical Surface'.
50 Newton, 'Fitzwilliam Notebook', 5[r]-9[v]. The purchase of Sprat's *History of the Royal Society* is on 6[v].
51 Newton, 'Fitzwilliam Notebook', 6[v].
52 Newton, 'Out of Philosophicall Transactions'.
53 *Philosophical Transactions* 2, no. 24 is dated 8 April 1667; see Lll1[r]. No. 25 is dated 6 May; see Nnn1[r].
54 Newton, 'Fitzwilliam Notebook', 6[r-v].

tools is the grinding of non-spherical lenses, especially as yet another manuscript from the period features notes on this very subject[55]. The following year he spent a shilling and four pence on putty, which may have served to polish a mirror destined for a reflecting telescope[56]. Then in 1669 he bought a furnace, having perhaps recognised that the best way of making progress was to start experimenting with his own metallic alloys[57]. Certainly, in a letter of that year to an unknown correspondent, he reveals that he has built a six-inch-long prototype, but admits that it does not represent objects distinctly, "by reason of bad Materialls"[58].

On 6 February 1672, shortly after his election to the Royal Society, Newton sent a letter to Henry Oldenburg, which was printed in the *Philosophical Transactions* and has since become famous as the first account of the experiments involving prisms by which he decomposed white light into the spectrum of colours[59]. As it is described in a previous communication, however, the goal of the letter is to provide the context for his invention of the reflecting telescope[60]. In the opening lines, meanwhile, Newton writes: "in the beginning of the Year 1666 (at which time I applied my self to the grinding of Optick glasses of other figures than *Spherical*,) I procured me a Triangular glass-Prisme, to try therewith the celebrated *Phænomena of Colours*"[61].

[55] Newton, 'Of Refractions', 561-7. In an editorial footnote, D.T. Whiteside tentatively dates the notes to winter 1665-66, based on the handwriting and on the account in Newton's letter of 6 February 1672; see 560n. The handwriting does not provide a particularly precise means of dating the document and, as I suggest in this section, the account in Newton's letter is not necessarily reliable. It seems reasonable to propose an alternative date, one that coincides with the purchase of the lathe.
[56] Newton, 'Fitzwilliam Notebook', 7^{r}.
[57] *Ibid*., 8^{r},
[58] Letter 3, dated 23 February, in Turnbull, Scott, Hall and Tilling, eds., *The Correspondence of Isaac Newton*, vol. 1, 3-9, at 3.
[59] Letter 40, in Turnbull, Scott, Hall and Tilling, eds., *The Correspondence of Isaac Newton*, vol. 1, 92-107. It was published in *Philosophical Transactions* 6, no. 80 (1672): Gggg1^{r}-Hhhh3^{r}. For a recent commentary on the letter and on responses to it, see Fara, 'Newton Shows the Light'.
[60] Letter 35, dated 18 January, in Turnbull, Scott, Hall and Tilling, eds., *The Correspondence of Isaac Newton*, 82-3. He promises "an accompt of a Philosophicall discovery, wch induced mee to the making of the said Telescope".
[61] Letter 40, in Turnbull, Scott, Hall and Tilling, eds., *The Correspondence of Isaac Newton*, vol. 1, 92.

The parenthetical comment turns out not to be incidental. After outlining the experiments that led him to his now celebrated theory of light, he declares his conclusion: “the perfection of Telescopes was hitherto limited, not so much for want of glasses truly figured according to the prescriptions of Optick Authors […] as because that Light it self is a *Heterogenous mixture of differently refrangible Rays*”[62]. The new theory, in this presentation of it, is not significant for its own sake, but because it allows a breakthrough in the field of optical instruments. Newton’s inspiration, as he describes it, was the recognition that all glass lenses are destined to suffer from chromatic aberration: even if it were perfectly ground, a lens shaped into a hyperbolic curve would still be subject to colours. He continues: “This led me to take *Reflections* into consideration […] I understood, that by their mediation Optick instruments might be brought to any degree of perfection imaginable”[63].

Newton’s account involves some chronological sleight of hand. His letter leaves the reader with the assumption that the invention of the reflecting telescope flowed naturally from his work with prisms, which coincided with his attempts to grind non-spherical lenses. It suggests that the essentials were in place by 1666, even if some details still required smoothing out. His experiments with prisms certainly date to this year, but, as we have seen, there is no evidence for any activity involving the grinding of lenses until 1667 and none for the construction of a reflecting telescope until 1668. Of course, he may simply have misremembered or he may have conducted work for which there is now no corroborating evidence. It hardly seems insignificant, however,

[62] *Ibid.*, 95.
[63] *Ibid.*, 95. For Newton’s thoughts on chromatic aberration, see Bechler, ‘A Less Agreeable Matter’.

that his account serves to place his invention safely before Francis Smethwick's new lenses and Robert Hooke's contracted telescope.

Not only does Newton's letter situate his invention before Royal Society activity in the same area; it also emphasises his instrument's superiority. His disdain for "glasses truly figured according to the prescriptions of Optick Authors" most obviously targets Descartes's suggestion for improved lenses, but it also acts as a dismissal of the recent attempts to realise the design, carried out by Francis Smethwick and subsequently by Christopher Wren and Robert Hooke. The claim to have dramatically altered the face of optical instrumentation certainly seems to have touched a nerve with Hooke. His critique of Newton's letter is principally concerned with the new theory of light, but he also writes: "I am a little troubled that this supposition should make Mr Newton wholly lay aside the thoughts of improving telescopes and microscopes by Refractions, since it is not improbable, but that he that hath made soe very good an improvement of telescopes by his own tryalls upon Reflection, would, if he had prosecuted it, have done more by Refraction"[64]. Hooke's generosity in acknowledging the impressiveness of Newton's invention may have been perfectly genuine, but there is an edge to this comment, given that the thrust of his critique is that Newton's experiments in no way prove his 'supposition' regarding the heterogeneous nature of light[65].

In fact, Newton's invention seems to have inspired Hooke, on the one hand to construct his own reflecting telescope, and on the other to return to his investigations into instruments that make use of the traditional Cartesian design. At a meeting of the Royal

---

[64] Letter 44, in Turnbull, Scott, Hall and Tilling, eds., *The Correspondence of Isaac Newton*, vol. 1, 110-6.
[65] For an overview of Hooke's critique, see Sabra, *Theories of Light*, 251-64.

Society on 18 January, the same at which Newton's telescope was first presented, he "made a Proposition of a highly considerable Improvement of all sorts of Optick and Burning-glasses". His proposal was lodged in a cipher, but the description in the minutes suggests that it involved picking up some of his former work on grinding non-spherical lenses; the new instruments are to feature "Lentes, of Figures as easily and perfectly made, as plain or Spherical"[66].

Another aspect of Newton's letter may have left Hooke feeling touchy. As part of his description of the reflecting telescope, Newton emphasises the importance of finding a metallic substance that will "polish as finely as Glass"[67]. He acknowledges that the problem is considerable; indeed, he stresses that he initially thought it insuperable. He evidently found a way of overcoming it, but in the letter to Oldenburg he provides no information about how he did so: his solution remains, perhaps designedly, just out of reach[68]. Of course, any Fellows of the Royal Society attending to this part of the document would have had a clear sense of the author's achievement: Newton had solved the problem that had scuppered Hooke's work five years previously.

Whether this part of the letter was written with an eye to Hooke's past failures or not, the Royal Society's Curator of Experiments seems to have felt subject to an implicit challenge. On 11 January, he declared his intention to build a reflecting telescope like Newton's[69]. He was, however, only partly successful. The instrument that he presented two weeks later was said to perform "pretty well", although the mirror "was not duly

[66] Royal Society MS JBO/ 4, 226. The proposal was registered as 'Proposition for the perfecting of Telescopes, Microscopes &c.', in Royal Society MS RBO/4, 121.
[67] Letter 40, in Turnbull, Scott, Hall and Tilling, eds., *The Correspondence of Isaac Newton*, vol. 1, 95.
[68] *Ibid*., 96.
[69] Royal Society MS JBO/4, 223-5, at 224.

polish'd"[70]. The attendees discussed possible alternative reflecting substances: Sir Robert Moray produced a small piece of opaque glass, made by Robert Boyle, and the young physician Edward Browne showed a black stone from Iceland, which had been sent to his father, Sir Thomas Browne[71]. A letter of advice that Newton had sent was read out, but the description of his search for a suitable substance proved, again, more tantalising than useful: the group was forced to ask Oldenburg to write back, "to let them know the proportions of those ingredients, he names, of Arsenick and Bell-mettal, he mentions in his letter"[72].

It is worth emphasising the extent to which Newton's achievement was a practical one. The design of his reflecting telescope was slightly different to those circulating at the time, but his real breakthrough lay in the construction of mirrors of sufficient reflecting power. His skill in the field that is now referred to by historians of science as 'chymistry' provided the basis for a leap forward in optical instruments[73]. As this emphasis on his talent in 'chymistry' makes clear, Newton's invention was the product of his particular abilities. But, as we have seen, there is evidence that his work was spurred on by his encounter with similar activity at the Royal Society. When he later came to communicate with the organisation, he seems to have taken steps to establish both his instrument's priority and its superiority. In fact, it is difficult to hold back from speculating that he may have thought of the reflecting telescope as a means of introducing himself. He had every reason to suspect that members of the body would

[70] Royal Society MS JBO/4, 227-8, at 227.
[71] *Ibid*., 227-8. For overviews of the lives and careers of Browne father and son, see Barbour, *Sir Thomas Browne*, and van Strien, 'Browne, Edward'.
[72] Royal Society MS JBO/4, 227. Newton's advice was sent on 18 January, in Letter 35, in Turnbull, Scott, Hall and Tilling, eds., *The Correspondence of Isaac Newton*, vol. 1, 82-3, at 82. He seems to have heard of Hooke's plan in a letter from Oldenburg, now lost. His reply to the Society's question is Letter 36, 84-5.
[73] For an introduction to the use of the consciously archaic term 'chymistry', see Newman and Principe, 'Alchemy vs. Chemistry'.

be impressed. Perhaps he thought it would ease the passage of his revolutionary idea about the composite nature of white light.

“[Y]e experiments I grownd my discours on destry all he has said about them”: Interference Colour and Newton’s Rings

If Newton hoped that, by sending a reflecting telescope to the Royal Society, he would facilitate the acceptance of his theory about the composite nature of light, he was soon disappointed. On 8 February, Henry Oldenburg reported that the letter outlining the theory had been read at a meeting of the Society and had “there mett both with a singular attention and an uncommon applause”[74]. But, at the following meeting, Robert Hooke produced his strongly worded critique, which was read aloud and sent on to Newton[75]. And he did not stop there: in the months that followed, he performed a number of experiments on a phenomenon, known to modern physicists as ‘interference colour’, which raises question marks about the explanatory power of Newton’s ideas. Unknown to Hooke, however, Newton had in fact been working on the same phenomenon and, in 1675, he was able to send a series of observations to the Royal Society. His experiments on what are now referred to as ‘Newton’s Rings’ flow naturally from his earlier work on the subject, but it is difficult not to view his communication of them in a polemical context: the new document that Newton dispatched to London most obviously functions as a riposte to Hooke’s objections[76].

The minutes for a Royal Society meeting held on 14 March 1672 record an experiment conducted by Robert Hooke, which was designed to highlight “a pretty phænomenon, in a Bubble raised by water and soap, wherein there appeared something on the top,

[74] Letter 41, in Turnbull, Scott, Hall and Tilling, eds., *The Correspondence of Isaac Newton*, vol. 1, 107-8, at 107.
[75] For an overview of Hooke’s critique, see Sabra, *Theories of Light*, 251-64.
[76] For an account of Newton’s work on rings, which does not foreground the polemical context, see Shapiro, *Fits, Passions and Paroxysms*, 49-97. For an older study, which pursues a similar angle to mine, see Westfall, ‘Newton’s Reply’.

that had neither reflection nor refraction, and yet was diaphanous"[77]. The subject under investigation is clearly light; meanwhile, the temporal proximity to Newton's letter of 6 February suggests that the experiment should be viewed as some kind of a response. The refraction of light in a glass prism, of course, plays a famous role in the Cambridge man's account of his new theory. When it comes to reflection, Hooke may have picked up on comments in one of the subsidiary propositions, regarding the colours of solid objects: "the Colours of all natural Bodies have no other origin than this," Newton writes, "that they are variously qualified to reflect one sort of light in greater plenty than another"[78]. In investigating something that demonstrates neither reflection nor refraction, then, Hooke may have had Newton in his sights. The comment in the Journal Book is, however, unhelpfully garbled. In modern usage, 'diaphaneity' is synonymous with 'translucence', but in the seventeenth century the word was commonly used to mean 'transparency'. Yet, it would hardly be surprising for a substance that does not reflect or refract light to appear transparent. The Royal Society's scribe (perhaps following Hooke) seems to have misused the term.

The confusion can be clarified with reference to the account of the experiment that Hooke brought in and lodged in the Register Book at the end of March[79]. In this description, the significant feature of a soapy bubble is not, in fact, transparency; he writes: "there appeared upon the surface thereof all variety of Colours that may be observed in a Rain-bow, beginning at first with a pale-yellow, then Orange, Red, Purple, Blue, Green, and so onward with other the same series or succession of

[77] Royal Society MS JBO/4, 238-9, at 239.
[78] Letter 40, in Turnbull, Scott, Hall and Tilling, eds., *The Correspondence of Isaac Newton*, vol. 1, 99-100, at 100.
[79] The meeting was on 28 March; see Royal Society MS JBO/4, 241-2, at 241.

Colours"[80]. Hooke seems to have derived a particular idea from Newton's expression of his theory of light: that all colour is the product either of reflection or of refraction. Here, he presents a phenomenon that, he claims, cannot be explained by these means. The point of the soapy bubble seems to be not to cast the new theory into doubt, but to challenge its explanatory power: how, Hooke is implicitly asking, does Newton's conception of light explain this peculiar phenomenon?

A week after he brought in the account of the colours present in a bubble, Hooke performed another experiment along the same lines, rubbing two plates of glass together and demonstrating "that there may be the same Incidence of rayes & yet various colours"[81]. A more detailed description appears in a report that he brought in and registered two months later, on 19 June: "I prest them hard together till there began to appeare a Red colour'd spot in the middle; then continuing to presse them closer, I could plainly see severall Rainbows (as I may soe call them) of colours"[82]. It is perhaps not a coincidence that he brought in this account on 19 June, one week after Newton's response to his critique had been read out before the Society[83].

In conducting experiments on bubbles and pieces of glass, Hooke was returning to work that he had initially described back in 1665. A chapter in *Micrographia* opens with a description of the colours visible on the surface of the mineral muscovite[84]. The author

[80] 'An Account of a Experiment or Observation made upon a Buble of Water and Soap, which at the first Appearance seems very strange', in Royal Society MS RBO/4, 128-9, at 128.
[81] Royal Society MS JBO/4, 243-4, at 243.
[82] 'An Accompt of some Experiments about Refractions & Colors', in Royal Society MS RBO/4, 194-6. The experiment is described on 195-6; the quote is from 195. For the meeting on 19 June, see Royal Society MS JBO/4, 255-6, at 255.
[83] Newton's response is Letter 67, in Turnbull, Scott, Hall and Tilling, eds., *The Correspondence of Isaac Newton*, vol. 1, 171-193. It was read out on 12 June; see Royal Society MS JBO/4, 254-255, at 255.
[84] Hooke, *Micrographia*, H4^r-L2^r, at H4^r-I1^r.

compares them to similar colours, observed in solid objects, such as steel, pearl and mother-of-pearl, as well as in glutinous liquids, such as pitch, rosin, colophony, turpentine, wort, wine, ethanol and (wonderfully) snail slime[85]. Among the solids, he includes plates of glass pressed together[86]; meanwhile, he introduces his list of liquids by mentioning bubbles of glass, if blown thin enough, as well as bubbles of soap-water[87]. Hooke prefaces his comments by explaining why he has compiled such a comprehensive inventory: "These *Phænomena* being so various, and so truly admirable, it will certainly be very well worth our inquiry, to examine the causes and reasons of them, and to consider, whether from these causes demonstratively evidenced, may not be deduced the true causes of the production of all kinds of Colours"[88]. The phenomena that he has identified, in other words, are not important in their own right; rather, their significance lies in the prompt that they provide for a comprehensive investigation into the nature of light and colours, one that takes up the remainder of this chapter and the following one[89].

Given his experience of such complex subject-matter, it is hardly surprising that Hooke's initial appraisal of Newton's work should be dismissive in tone, especially if, as he later claimed in a letter to Viscount Brouncker, he had prepared his response in haste[90]. After all, however precise Newton had been in his analysis of the colours in a prism, he had made no attempt to engage with the more complicated phenomena described in *Micrographia*. In his critique, Hooke does not highlight the absence of

---

85 *Ibid*., I2^{r} and I3^{r}.
86 *Ibid*., I1^{v}.
87 *Ibid*., I2^{r}.
88 *Ibid*., I1^{r}.
89 *Ibid*., I1^{r}-L2^{r}, and L2^{r}-M4^{r}.
90 Letter 71, in Turnbull, Scott, Hall and Tilling, eds., *The Correspondence of Isaac Newton*, vol. 1, 198-205. He writes: "I had not above three or 4 hours times for the perusal of Mr. Newtons paper and the writing of my answer", 198. The letter is undated, but was presumably sent shortly after Newton's response to Hooke's critique.

these colours explicitly, but he concludes with a suggestion that hints at the grounds for his dismissiveness: "I believe, Mr Newton will think it noe difficult matter by my hypothesis to salve all the phænomena, not only of the prisme, tingd liquors and solid bodys, but of colours of plated bodys, which seem to have the greatest difficulty"[91].

The irony in Hooke's critique is that Newton had, in fact, been prompted by his reading of *Micrographia* to investigate these very phenomena[92]. Indeed, he seems to have gone a step further and taken a geometrical approach to the coloured rings produced by two plates of glass, by using one with a curved and another with a plane surface[93]. Notes on an investigation made using this equipment feature in the 1666 manuscript essay 'Of Colours'[94]. The technology then re-appears in a collection of rough propositions and experiments, dating to the early 1670s, which forms the basis for a series of observations, entitled 'Of the Colours of Plated Transparent Substances'[95].

This series of observations is presumably the "discourse" on "the Phænomena of Plated Bodies" that Newton mentions in a letter to Oldenburg of 21 May 1672[96]. He writes that he will send the document to the Royal Society, but seems to have changed his mind. No reference to his work on the subject appears in the response to Hooke's critique, sent in June; in fact, he makes no further mention of it at all until December

---

[91] Letter 44, in Turnbull, Scott, Hall and Tilling, eds., *The Correspondence of Isaac Newton*, vol. 1, 114.
[92] For the relationship of Newton's work with the comments in *Micrographia*, see Shapiro, *Fits, Passions and Paroxysms*, 57-9.
[93] See Shapiro, *Fits, Passions and Paroxysms*, 53-4.
[94] Newton, 'Of Colours', 476-7. See Shapiro, *Fits, Passions and Paroxysms*, 54-6.
[95] Newton, 'Of y^e Coloured Circles', and 'Of the Colours of Plated Transparent Substances'. For a discussion of the works, see Shapiro, *Fits, Passions and Paroxysms*, 59-72.
[96] Letter 62, in Turnbull, Scott, Hall and Tilling, eds., *The Correspondence of Isaac Newton*, vol. 1, 159-160, at 160.

1674, when in another letter to Oldenburg he refers casually to "something by me", which could provide the Society with material for "a vacant week or two"[97].

The following spring saw Newton's first attendance at a Royal Society gathering, on 18 February 1675[98]. The minutes for a meeting held three weeks later, on 11 March, feature an intriguing entry: "The person, that should haue made a Discourse this day, being by urgent occasions kept from the Society, there was read out of the Register a Discourse formerly given in my Mr. Boyle, about shining Flesh"[99]. It looks as if the Society may have taken up Newton's offer to provide something for a vacant week, but, for one reason or another, he proved unable to deliver and the Fellows were forced to plunder the Register Book for other interesting material about light[100].

Newton's discourse rears its head yet again in a letter sent to Oldenburg from Cambridge that November[101]. At the end of the month, he excuses himself for not yet having sent it, explaining that he had the idea of preparing a supplementary "little scribble", and promising that he will dispatch both pieces the following week[102]. The document, comprising a long series of observations on coloured rings followed by some conclusions, was finally sent to London on 7 December 1675[103]. It arrived together with

---

97 Letter 129, dated 5 December, in Turnbull, Scott, Hall and Tilling, eds., *The Correspondence of Isaac Newton*, vol. 1, 328-9, at 328.

98 He was formally admitted on this date; see Royal Society MS JBO/5, 95-7, at 95.

99 Royal Society MS JBO/5, 101.

100 Robert Boyle's observations of a glowing piece of veal had been registered on 21 March 1672; see Royal Society MS JBO/4, 240, and 'Some Observations about Shining Flesh', in Royal Society MS RBO/4, 130-7.

101 Letter 143, dated 13 November, in Turnbull, Scott, Hall and Tilling, eds., *The Correspondence of Isaac Newton*, vol. 1, 356-9, at 358.

102 Letter 144, dated 30 November, in Turnbull, Scott, Hall and Tilling, eds., *The Correspondence of Isaac Newton*, vol. 1, 359-60, at 359.

103 Newton, 'Mr. Isaac Newtons Observations'. I refer to the copy in the Royal Society's Register Book, with the idea that this is the document that Society members would have had access to. The more common source – referenced, for example, in Shapiro, *Fits, Passions and Paroxysms*, 60n. – is the copy that Newton retained, Cambridge University Library MS Add. 3970, 501r-17r. There are, in any case, no significant differences.

a much shorter text, outlining a hypothesis concerning the properties of light, presumably the “little scribble” that Newton had mentioned[104].

Perhaps unsurprisingly, the Royal Society decided to start with the shorter document, the first half of which was read out at a meeting on 9 December[105]. In the opening pages, Newton sets out the purpose of the piece: “I have here thought fitt to send you a description of the circumstances of this Hypothesis”, he writes, for the reason that “I have observed the heads of some great virtuosos to run much upon Hypotheses”[106]. The reference is almost certainly to Hooke; in Newton’s response to Hooke’s critique, dispatched back in June 1672, he had observed: “I was a little troubled to find a person so much concerned for an *Hypothesis*, from whome in particular I most expected an unconcerned & indifferent examination of what I propounded”[107].

Newton consistently made a distinction between the terms ‘theory’ and ‘hypothesis’, using the first to refer to what Alan Shapiro has called “rigorously demonstrated principles”, and reserving the second for “conjectural causal explanation”[108]. The irritation evident in his response to Hooke’s critique results from the latter’s slide from the ‘theory’ that light is comprised of colours, which is founded on the experiments with prisms included in the treatise, to the ‘hypothesis’ that it is corpuscular, which is not. Hooke was, however, not the only correspondent to fall foul of Newton’s

---

[104] Newton, ‘An Hypothesis explaining the Properties of Light’. The communication enclosing the ‘Observations’ and the ‘Hypothesis’ is Letter 145, in Turnbull, Scott, Hall and Tilling, eds., *The Correspondence of Isaac Newton*, vol. 1, 360-3.
[105] Royal Society MS JBO/5, 131-4, at 132-3. Alan Shapiro attributes the decision, unnecessarily in my view, to Oldenburg’s desire to stoke a quarrel between Hooke and Newton; see ‘Twenty-Nine Years in the Making’, 425-6. For a discussion of the work, see Shapiro, *Fits, Passions and Paroxysms*, 72-89.
[106] Newton, ‘An Hypothesis explaining the Properties of Light’, 363.
[107] Letter 67, in Turnbull, Scott, Hall and Tilling, eds., *The Correspondence of Isaac Newton*, vol. 1, 171-93, at 171.
[108] For an overview of Newton’s methodology, as it is appears in his optical work, see Shapiro, ‘Newton’s Optics and Atomism’; the quotes are, respectively, from 227 and 228.

exactitude in this use of terminology. Having referred to the theory as a 'hypothesis' in a letter to Oldenburg, the Jesuit philosopher Ignace-Gaston Pardies found himself the subject of a mild rebuke: "I am content that the Reverend Father calls my theory an hypothesis if it has not yet been proved to his satisfaction. But […] it seems to contain nothing else than certain properties of light which, now discovered, I think are not difficult to prove"[109]. In a subsequent letter, Pardies felt compelled to apologise: "In calling this theory a hypothesis […] I used the first word to spring to mind"[110].

In his 1675 communication with the Royal Society, Newton does not address the earlier misunderstandings directly, but the inclusion of a hypothesis alongside his discourse of observations could be viewed as an attempt to forestall the kind of objections that had hindered the acceptance of the theory about the composite nature of light. This time, in a separate document, he sets out a hypothesis, all the while stressing its independence from the theories established by his experiments.

Given the hypothetical character of the piece, the response of the Royal Society members who heard it read aloud on 9 December is perhaps a little surprising: "Some of the Company taking particular notice, among other things, of an Experiment mentioned in this Hypothesis; desired it might be tryed"[111]. The experiment in question involves rubbing a piece of glass that is suspended in a brass ring above a table and

[109] *Quòd R.P. Theoriam nostram Hypothesin vocat, amice habeo, siquidem ipsi nondum constet. Sed* […] *nihil aliud continere videtur quàm proprietates quasdem Lucis, quas jam inventas probare haud difficile existimo*, Letter 55, dated 13 April 1672, in Turnbull, Scott, Hall and Tilling, eds., *The Correspondence of Isaac Newton*, vol. 1, 140-4, at 142, translated on 144. Pardies's mistake is in Letter 52, 130-4. For an overview of his optics and his correspondence with Newton, see Ziggelaar, *Le physicien Ignace Gaston Pardies*, 170-86.
[110] *Quod autem Theoriam istam apellarim* Hypothesim […] *nomen usurpavi quod primum occurrit*, Letter 61, dated 11 May, in Turnbull, Scott, Hall and Tilling, eds., *The Correspondence of Isaac Newton*, vol. 1, 156-159, at 158, my translation.
[111] Royal Society MS JBO/5, 131-4, at 133.

observing the attraction and repulsion of small pieces of paper[112]. Newton attributes the phenomenon to the presence of "electric effluvia", which he uses as evidence of "an ætheriall Medium much of the same constitution with air, but far rarer, subtiler & more strongly Elastic"[113]. After describing his understanding of this ætherial medium, he presents some thoughts about how light could interact with it in such ways as to result in reflection, refraction, transparency and opacity[114].

At the following meeting, the Royal Society attempted to replicate Newton's experiment. Having heard of the plan, the man himself sent some advice, along with the admission: "I began to suspect yt I had set down a greater distance of ye glas from ye table then I should have done"[115]. Despite the advice and the *mea culpa*, however, the repetition of the trial failed and the company entertained itself by reading the second half of the 'Hypothesis', in which Newton brings his thoughts about the interaction of light and æther to bear on the appearance of colours[116]. Robert Hooke apparently felt bold enough to declare: "the main of it was contained in his Micrography, which M^{r}. Newton in some particulars onely had carried further"[117].

Newton sent another letter on 21 December, in which he provides some further guidance on how to go about the experiment, as well as a strongly worded rebuttal of Hooke's claim[118]. The guidance was read out after Christmas and another attempt was

---

112 Newton, 'An Hypothesis explaining the Properties of Light', 364.
113 *Ibid.*, 364.
114 *Ibid.*, 371-6.
115 Letter 147, in Turnbull, Scott, Hall and Tilling, eds., *The Correspondence of Isaac Newton*, vol. 1, 392-3, at 392.
116 Royal Society MS JBO/5, 134-5. The second half of the 'Hypothesis' is 376-386.
117 Royal Society MS JBO/5, 135.
118 Letter 150, in Turnbull, Scott, Hall and Tilling, eds., *The Correspondence of Isaac Newton*, vol. 1, 404-7. The guidance is on 404-5; the rebuttal of Hooke's claim is on 405-6.

scheduled for the following meeting[119]. Interestingly, the Society did not at this point proceed to examine the discourse of observations that Newton had sent alongside his hypothesis. Of course, time may have been short and other business deemed more pressing. It does, though, look a little as if the assembled Fellows were unwilling to move on to a lengthy discussion of experimental activity, while its author's practical credentials were potentially subject to question. When the Society reconvened on 13 January 1676, however, Newton's updated guidance was followed carefully and the experiment produced exactly the results that he had described[120]. Any doubts that may have arisen about his practical competence were assuaged and, the following week, the Society began a consideration of his collection of observations[121].

Newton opens his discourse by establishing the context: "I suppose you understand that all transparent substances (as Glasse, water, Aire, &c) when made very thin by being blowne into Bubbles or otherwise formed into Plates, doe exhibite various colours according to their various thinness"[122]. The experiments that follow, like his previous studies of the subject, involve the colours produced by two plates of glass pressed together, one with a curved surface and one with a plane surface. The reference to bubbles, however, serves to tie the work to Hooke's remarks in *Micrographia* and to the experiment conducted before the Royal Society in 1672.

The piece continues with an explanation of why he has not discussed these colours before: "they seemed of a more difficult consideracõn, and were not necessary for the

---

[119] The meeting was on 30 December; see Royal Society MS JBO/5, 135-6, at 135.
[120] Royal Society MS JBO/5, 136-7, at 136.
[121] The meeting was on 20 January; see Royal Society MS JBO/5, 137-9. For a discussion of the work, see Shapiro, *Fits, Passions and Paroxysms*, 62-72.
[122] Newton, 'M^{r}. Isaac Newtons Observations', 89.

Establishing of the Doctrine w^{ch}. I propounded". The comment serves to emphasise that his earlier work on light had not been in any way insufficient: the fact that he had not dealt with the colours that he is shortly to consider does not, he insists, invalidate his previous statement of light's heterogeneous nature. On the contrary, he concludes, he has now sent a discussion of these particular phenomena, "because they may conduce to further Discoveryes for compleating that Theory"[123].

Newton's experimental approach is characterised in this case, as elsewhere, by an exhaustive series of extraordinarily precise measurements, so it is perhaps not surprising that the attendees who were gathered to hear his discourse interrupted it after the first fifteen observations. They moved on to what is undoubtedly more entertaining material: that part of the letter of 21 December, in which Newton had laid out a rebuttal of the claim that he had added nothing substantial to the investigation in *Micrographia*[124]. In this letter, he describes in detail how his work differs from Hooke's and, although they had only heard the beginning of the discourse of observations, it seems unlikely that any Fellows present would have been prepared to contradict the assertion: "in ye colours of thin transparent substances […] ye experiments I grownd my discours on destry all he has said about them"[125].

After the meeting, Hooke clearly felt the need to write a conciliatory message to Newton. He places the blame for any conflict that may have arisen on Henry Oldenburg and insists, a little implausibly: "I have a mind very desirous of and very ready to imbrace any truth that shall be discovered though it may much thwart and contradict

[123] *Ibid.*, 89.
[124] Royal Society MS JBO/5, 138.
[125] Letter 150, in Turnbull, Scott, Hall and Tilling, eds., *The Correspondence of Isaac Newton*, vol. 1, 405.

any opinions or notions I have formerly imbraced as such"[126]. The aim of the letter is evidently to defuse the tension existing between the two men, but it is worth noting how careful Hooke's phrasing is: he stresses his readiness to embrace any truths, no matter how much they may challenge his thoughts, without ever suggesting that the truths in question are those put forward by Newton.

Curiously, the minutes for the meeting held the following week include no mention of Newton's discourse: it may have been overlooked, or it could be that the company heard the remaining ten observations, without the fact making it into the Journal Book[127]. The next reference is in the minutes for 3 February, when the Society attended to the section in which Newton discusses the preceding observations, a discussion that depends on a theory of 'ætherial vibrations', his explanation for the periodicity of light[128]. He concludes, by emphasising the connection between his work on interference colour and the theory of light that he had laid out three years previously: "These are the Principall Phænomena of thin plates or Bubble, whose Explications depend on the Properties of Light that I have heretofore delivered"[129].

When it was read aloud, this part of Newton's discourse apparently prompted a debate at the Royal Society about the earlier theory of light; the question was whether the presence of different colours could be explained by "the several degrees of the Velocity of Pulses, rather than (as M[r]. Newton esteems) to the several connate degrees of

[126] Letter 152, dated 20 January, in Turnbull, Scott, Hall and Tilling, eds., *The Correspondence of Isaac Newton*, vol. 1, 412-4, at 412. Newton's response, sent on 5 February, is Letter 154, 416-7.
[127] Royal Society MS JBO/5, 139-40.
[128] Newton, 'M[r]. Isaac Newtons Observations', 102-12. See Shapiro, *Fits, Passions and Paroxysms*, 60-1, 69, and 72-3.
[129] Newton, 'M[r]. Isaac Newtons Observations', 111. The discourse features a final section, in which Newton extends his discussion to the colours of solid bodies; see 113-124. It was read before the Royal Society on 10 February; see Royal Society MS JBO/5, 141-3, at 143. For Newton's work on the subject, see Shapiro, *Fits, Passions and Paroxysms*, 98-135.

refrangibility in the Rayes themselves". The minutes report: "Mr. Hook was of opinion, that the former of these wayes was sufficient to giue a good account of the diversity of Colours"[130]. The point was clearly reported to Newton as an objection: in a letter of 15 February, he replies to Oldenburg that, on the contrary, it is "not an objection but an Hypothesis to explain my Theory"[131]. He goes on to set out a "general rule", in order to "cut off all objections that may be raised for ye future either from this or any Hypothesis whatever". This rule, he continues, will be familiar to those who have followed his previous correspondence with Ignace-Gaston Pardies and Robert Hooke: "in any Hypothesis whence ye rays may be supposed to have any originall diversities, whether as to size or figure or motion or force or quality or any thing els imaginable wch may suffice to difference those rays in colour & refrangibility, there is no need to seek for other causes of these effects then those original diversities"[132].

Newton's phrasing here echoes the cautious tone adopted in the hypothesis that he had sent alongside his discourse of observations. There, he presents a hypothetical discussion of some of the properties of light, in which he is notably vague about what light actually is: "I suppose Light is neither this Æther nor its vibrating motion", he writes, "but something of a different kind propagated from lucid bodies". The closest he comes to describing this "something of a different kind" is as follows: "I would suppose, it consists of Successive rayes differing from one another in contingent circumstances, as bignes, forme or vigour, like as the Sands on the Shore, the waves of the Sea, the faces of men, & all other naturall things of the same kind differ"[133].

---

130 Royal Society MS JBO/5, 140-1, at 141.
131 Letter 155, sent on 15 February, in Turnbull, Scott, Hall and Tilling, eds., *The Correspondence of Isaac Newton*, vol. 1, 417-21, at 417. Oldenburg's letter is lost.
132 *Ibid.*, 419-20.
133 Newton, 'An Hypothesis explaining the Properties of Light', 370.

The tone of the letter that Newton dispatched on 15 February 1676 is surprisingly pleasant, given that he had every reason to be exasperated. In a bid to forestall any misconceptions about his working practice, he had accompanied his observations of coloured rings with a hypothesis, in which he had laid out his speculative thoughts about light. But his methods continued to be misunderstood. Rather than examine the details of his practical work or engage with the explanation of interference colour that is based on it, Hooke offered an objection that was not, Newton insists, an objection, but a hypothesis about light, one, moreover, that in no way contradicted his own. If Newton thought that his experiments would destroy any opposition that Hooke could muster, he was disappointed: the latter turned out to be remarkably resilient.

“[H]aving not made sufficient observation”: Diffraction and Æther

In his first exchange of letters with Henry Oldenburg, Newton seems keen to be involved in Royal Society activity. On 6 January 1672, for example, he expresses his gratitude at having been nominated for membership[134]; on 18 January, having been elected, he enquires about his responsibilities[135]. Yet, for many years his engagement with the organisation was limited: he continued to correspond with Oldenburg and other Society members, but he did not become a regular contributor to the body’s weekly meetings until November 1703, when he was elected its President[136].

Earlier that year, Robert Hooke had died. The event seems to have provided an opportunity for Newton, not only clearing the way for an increased involvement in Royal Society activity, but also allowing the release, in 1704, of his work on optics to the literate public[137]. An obvious reason for his delay in publishing a volume detailing his work in the field is a general sense of unease about Hooke’s likely response. In particular, he may have been concerned that the Royal Society’s famous experimentalist would sink his teeth into the material in the third section, which focuses on a new feature of light: diffraction. If so, Hooke’s departure from the scene seems not to have offered the respite that he had hoped for: indeed, to some extent, he appears to have been haunted by the spectre of his rival’s posthumous judgement.

134 Letter 33, in Turnbull, Scott, Hall and Tilling, eds., *The Correspondence of Isaac Newton*, vol. 1, 79-81, at 80.
135 Letter 35, in Turnbull, Scott, Hall and Tilling, eds., *The Correspondence of Isaac Newton*, vol. 1, 82-3, at 83.
136 He was elected President on 30 November 1703; see Royal Society MS JBO/11, 36-7, at 36. Aside from Oldenburg, his most prominent correspondents were John Collins and Edmond Halley: see Scriba, ‘Collins, John’, and Cook, *Edmond Halley*, 147-78.
137 Newton, *Opticks*. For introductions to the work, see Hall, *All Was Light*, and Shapiro, ‘Twenty-Nine Years’.

As mentioned in the previous section, Newton first attended a meeting of the Royal Society on 18 February 1675, three years after he dispatched his reflecting telescope and his thoughts on the heterogeneous nature of light to London[138]. At the meeting held three weeks later, at which he (if it was he) was unexpectedly unable to deliver the discourse that he had promised, the Fellows present entertained themselves with Robert Boyle's observations of a glowing piece of veal, which occasioned a debate about the nature of light. Hooke, as usual, was not shy in putting forward his thoughts on the subject. He was, furthermore, reminded of an interesting phenomenon, which he remembered having described in a discourse that he had presented, but not left to be registered. He was encouraged to bring it in again at the next meeting[139].

The piece in question, presented the following week, begins with a lengthy passage in praise of experimentation, before describing an investigation conducted in a room from which all light has been excluded, bar a single beam[140]. Hooke observes that, when the light is projected onto a piece of paper, it is surrounded by what he refers to as a dark 'penumbra'[141]. He then places an item – first a round piece of wood, then a razor blade – in the beam and notes that light is cast into the shadow of the object[142]. He concludes: "it was very manifest, that it was some new Propriety of Light much differing from the common Rules and Laws thereof deliver'd in Optical and Physical Writers"[143]. He calls this new property 'deflection'; it is known today as 'diffraction'.

[138] Royal Society MS JBO/5, 95-7, at 95.
[139] Royal Society MS JBO/5, 101. The reference is probably to a discourse read on 27 November 1672; see MS JBO/4, 268-9, at 268.
[140] Hooke, 'A Lecture on Light'. The praise of experimental practice is Bbb1^{v}; the description of the set-up is Bbb1^{v}-Bbb2^{r}. He presented it on 18 March; see Royal Society MS JBO/5, 102-3.
[141] *Ibid.*, Bbb2^{r}.
[142] *Ibid.*, Bbb2^{r-v}.
[143] *Ibid.*, Bbb2^{v}.

Hooke's experiment challenges one of the fundamental assumptions held by optical thinkers of the period: that light proceeds in straight lines[144]. In June 1672, Newton had drawn on this assumption in his response to Hooke's critique of his theory of light; in a section devoted to the latter's wave model, he writes: "to me the fundamental supposition it selfe seemes impossible; namely that the waves or vibrations of any fluid can like the rays of Light be propagated in straight lines, without a continuall & very extravagant spreading & bending every way into ye quiescent Medium"[145].

The experiment with an object in a beam of light, then, functions as a defence of Hooke's idea: it suggests that light does, in fact, spread and bend in the air like a wave. But it also acts as a challenge for Newton. Like the experiments that Hooke conducted with bubbles and plates of glass, it is not sufficient to cast Newton's work into doubt, but, like those experiments, it raises questions about its explanatory power. Indeed, Hooke seems to have recognised its potential to act in this way: in the account of his critique that he sent to Viscount Brouncker in June 1672, after the reception of Newton's response, he suggests: "if Mr. Newton try ye Experiment I am very confident he will ascribe that deflection of ye Rayes neither to Reflection nor Refraction"[146].

In fact, when Newton encountered the experiment contained in Hooke's discourse at the meeting of the Royal Society at which the latter was presented, he apparently did ascribe the movement of the beam to refraction. In the second part of the 'Hypothesis' concerning light that he sent later that year, he recapitulates Hooke's description of the

[144] For an overview of the discovery, which Hooke may have taken from the Italian natural philosopher Francesco Maria Grimaldi, see Hall, 'Beyond the Fringe', 13-5.
[145] Letter 67, dated 11 June, in Turnbull, Scott, Hall and Tilling, eds., *The Correspondence of Isaac Newton*, vol. 1. The discussion of Hooke's model is 174-6; the quote is on 175.
[146] Letter 71, in Turnbull, Scott, Hall and Tilling, eds., *The Correspondence of Isaac Newton*, vol. 1, 200-1.

phenomenon, as well as his own response: “I took it to be onely a new kind of refraction, caused perhaps by the externall æthers beginning to grow rarer a little before it come at the Opake body, then it was in free spaces”[147]. He goes on to discuss the account of a similar experiment included in Honoré Fabri’s dialogue ‘De lumine’[148]. But, he concludes: “I have no time left to insist further on particulers; Nor do propound this without diffidence, having not made sufficient observation about it”[149].

Newton returned to the phenomenon in the late 1680s, when he came to prepare his work on optics for the press[150]. His first step, recorded in brief manuscript observations, was to repeat Hooke’s experiment with a razor in a beam of light, but he also proceeded to add a second blade[151]. The work is evidently at an early stage: his notes include no measurements – the manuscript leaves gaps where they are to be copied in – and are followed by three simple, single-line ideas for further activity[152]. Moreover, he clearly still thought of the movement under investigation as a kind of refraction; he opens with the statement: “light in its passage by bodies whether opake or transparent is refracted without entring into y^{e} refracting bodies”[153].

Other manuscript fragments show Newton developing his work with two blades and conducting new observations on the shadow cast by a human hair[154]. He introduces

147 Newton, ‘An Hypothesis explaining the Properties of Light’, 383.
148 *Ibid.*, 384; the reference is to Fabri, ‘De lumine’, A2^{v}-A3^{r}.
149 Newton, ‘An Hypothesis explaining the Properties of Light’, 385. For discussions of Newton’s early take on diffraction, see Stuewer, ‘A Critical Analysis’, 189-95, and Hall, ‘Beyond the Fringe’, 15-9.
150 For an overview of his work on diffraction at this point, which does not stress the polemical context, see Shapiro, ‘Newton’s Experiments on Diffraction’. For a discussion of the drafting of the *Opticks*, see Shapiro, ‘Beyond the Dating Game’, 198-222.
151 Newton, ‘Of the Refraction of Light in its Passage by Bodies’, 371^{r-v} and 372^{r-v}. For a discussion of the second experiment, see Shapiro, ‘Experiments on Diffraction’, 50.
152 Newton, ‘Of the Refraction of Light in its Passage by Bodies’, 372^{v}.
153 *Ibid.*, 371^{r}.
154 Newton, ‘Observations of Two Blades’ and ‘Of the Inflexion of Light’. For a discussion of the experiments with a hair, see Shapiro, ‘Experiments on Diffraction’, 52-60.

these observations on a hair with what he calls a ‘proposition’: “The surfaces of bodies act regularly upon the rays of Light at a Distance on both sides so as to inflect them variously according to their several degrees of refrangibility, & distances from the surface”[155]. One aspect of the statement worth noting is the apparent decision that Hooke was right to characterise the movement as a distinct property of light, which Newton here terms ‘inflection’. Another significant point is the absence of the æther, to which he had attributed action at a distance in the earlier ‘Hypothesis’.

Shortly afterwards, Newton prepared a fair copy of all the work that he had conducted in the area thus far. Again, he refers to the movement of light as ‘inflection’, but this time he limits himself to a series of observations of the phenomenon: not only is there no mention of a hypothetical æther; there is no proposition[156]. The effort to stay close to the data has not, however, prevented Alan Shapiro identifying the presence of a hypothesis lurking behind Newton’s presentation of his results. Shapiro calls it the ‘linear propagation model’, according to which, after being bent at a point near the object, the rays of light proceed in a straight line and produce a rectilinear fringe[157].

Newton completed the fair copy of his investigations at some point in the autumn of 1691 and, with it, he had a complete draft of his work in optics ready to go to press[158]. But he did not stop experimenting and, around February 1692, he hit a serious problem. Having carried out further trials on a beam of light cast between two blades, he noticed that the light forming a fringe can be light deflected at different angles from the blade:

---

[155] Newton, ‘Of the Inflexion of Light’, 377^{r}.
[156] Newton, ‘Observations concerning the Inflexions of the Rays of Light’. For a discussion of the observations, see Shapiro, ‘Experiments on Diffraction’, 60-5.
[157] Shapiro, ‘Experiments on Diffraction’, 54-6.
[158] For the dating, see Shapiro, ‘Beyond the Dating Game’, 210-3.

in other words, the rays of light and the fringe are not identically rectilinear[159]. The result does not invalidate the observations that he had conducted, but it undermines the linear propagation model that had guided them: it revealed, in short, that his understanding of the phenomenon was fundamentally flawed.

Why did Newton not persevere? After all, he had encountered problems in his previous investigations of light and successfully overcome them. Alan Shapiro suggests a simple reason: he was approaching the end of his active scientific career[160]. My explanation is a slightly nuanced version of the point. The experiment of February 1692 not only highlighted the deficiency in his comprehension of diffraction; it also presented a challenge to his ideas about the interactions between light and æther. He does not explicitly mention æther in the developed versions of his thoughts, but the fact that diffraction involves action at a distance seems to require its tacit presence, or at least some means of explaining action at a distance[161]. Perhaps, for the 50-year-old natural philosopher, the thought of an inquiry that threatened to overturn his entire hypothetical understanding of the properties of light was a step too far.

In any case, what is clear is that the book was not publishable in the form that it took in 1692. Based on his previous experiences, Newton had every reason to believe that Hooke would leap on the absence of any discussion of diffraction, just as much as on an investigation that was inadequate. He may well have intended to return to the subject

[159] The results of the experiment are reported in Cambridge University Library MS Add. 3970, 334^{r}. For a discussion, see Shapiro, 'Experiments on Diffraction', 65-6.
[160] Shapiro, 'Experiments on Diffraction', 67, and 'Twenty-Nine Years', 434.
[161] Newton's thoughts on action at a-distance have been much discussed of late, although not with reference to his work on diffraction; for an overview of the terrain, see Ducheyne, 'Newton on Action at a Distance', 678-82.

at some point and give it the attention that it deserved, but to all intents and purposes he spent the next decade simply waiting[162].

Robert Hooke died on 3 March 1703. The organisation to which he had devoted so much time and energy seems not to have marked the event with any great solemnity; the minutes of the meetings held in the following weeks simply note the items of interest recovered from his lodgings[163]. On 5 May, the task of going through his papers was assigned to Richard Waller, an obvious choice: as well as a secretary of the Royal Society, Waller was a close friend of the deceased[164]. Later in the year, he brought in and showed the results of his sifting: a scheme for improving natural philosophy and a series of lectures on light. He was encouraged to print both documents[165].

At a meeting held in February 1704, one of Newton's first significant acts as the new President of the Royal Society was to present the organisation with a copy of his freshly printed *Opticks*[166]. The book is in three parts, which, very generally speaking, lay out his theory of light of 1672, his analysis of interference colour of 1675 and his investigation of diffraction[167]. In a thinly veiled reference to Hooke, he explains in the opening 'Advertisement' that he has not previously published his work in the field, in

---

[162] Alan Shapiro mentions the idea, suggested to him by A.I. Sabra, that Newton's fear of Hooke's likely response may have played a role in delaying the publication of the *Opticks*, but he dismisses it; see 'Experiments on Diffraction', 70 and 75-6n.
[163] These items include two white, triangular stones taken from the bowels of an ox, a large snake's skin, and volumes of the Journal Book, Register Book and Council Minutes; see the minutes for meetings on 31 March and 7, 14, and 28 April, Royal Society JBO/11, 16-17, at 17, 17, 18 and 19-20, at 20.
[164] Royal Society JBO/11, 20-21, at 20. For an overview of Waller's life and career, see Mulligan, 'Waller, Richard'.
[165] The meeting was on 17 November, shortly before Newton's election as President; see Royal Society JBO/11, 34-5, at 34.
[166] The meeting was on 16 February; see Royal Society MS JBO/11, 42-3, at 43.
[167] Most obviously, this schematisation ignores Newton's work on the colour of thick plates, for which see Shapiro, *Fits, Passions and Paroxysms*, 150-71.

order to “avoid being engaged in Disputes about these Matters”[168]. The comment can be viewed as the expression of a general desire not to open old wounds, but it could also reflect a particular wish not to expose himself to a new attack on his work on diffraction. With Hooke out of the picture, he seems to have been more comfortable releasing his thoughts on the subject, even though they remained incomplete. The pre-publication revisions that he made to the section on diffraction consist simply of removing any allusions to the linear propagation model and adding the experimental results that had invalidated it[169]. He closes the section with a somewhat bland *caveat lector*: “When I made the foregoing Observations, I designed to repeat most of them with more care and exactness, and to make some new ones […] But I was then interrupted, and cannot think of taking these things into further consideration”[170].

Instead, Newton ended the book with what has become one of the most famous parts of his *œuvre*: a series of speculative queries[171]. Initially, the subject of inquiry is clearly diffraction, but the author moves on to topics of little obvious relevance, including heat and vision[172]. Such a range of material is reflected in the manuscript antecedent to the queries: three drafts of a succession of propositions, all dating to 1691[173]. Again, Newton starts with an evident interest in diffraction[174]; again, however, he goes on to consider other things, including (once more) heat and vision[175].

[168] Newton, *Opticks*, [*]$^{r-v}$, at [*]^{r}.
[169] For a discussion of the changes, see Shapiro, ‘Experiments on Diffraction’, 67-9.
[170] Newton, *Opticks*, Ss2^{v}.
[171] *Ibid.*, Ss2^{v}-Tt1^{r}. For an overview of the queries, see Hall, *All Was Light*, 127-62.
[172] Diffraction is the subject of queries one to three; see Newton, *Opticks*, Ss2^{v}-Ss3^{r}. Broadly conceived, heat is the subject of queries six, seven, eight, and eleven; see Newton, *Opticks*, Ss3^{r} and Ss4^{r}. Vision is the subject of queries twelve to sixteen; see Ss4^{r}-Tt1^{r}.
[173] Newton, ‘The Fourth Book’. The first draft is 342^{r-v} and 341^{r-v}; the second is 337^{r}-338^{v}; a fair copy is 335^{r}-336^{v}. For the dating, see Shapiro, ‘Beyond the Dating Game’, 210-1. For a discussion of the documents, see Shapiro, *Fits, Passions and Paroxysms*, 141-3.
[174] Newton, ‘The Fourth Book’, 342^{r}, 337^{r} and 335^{r}.
[175] Heat appears in ‘The Fourth Book’, 338^{r} and 335^{v}; vision is on 342^{r}, 337^{v} and 335^{v}.

It is tempting to ascribe these apparent digressions to a snowballing effect: once Newton had allowed himself to begin speculating, the argument runs, he simply found it difficult to stop[176]. The manuscript drafts, however, feature an attempt to bring the disparate material together; the fair copy ends with a hypothetical conclusion: "The particles of bodies have certain spheres of activity wthin w^{ch} they attract or shun one another"[177]. The comment could simply be a *post hoc* rationalisation of what would otherwise be a jaunt through diffuse subject-matter. Alternatively, the subject-matter could be diffuse, because the investigation is a general one: Newton seems to have been pursuing an interest in phenomena involving action at a distance.

In the transition from manuscript to print, the concluding hypothetical remarks were dropped and the statements downgraded from propositions to queries: perhaps Newton was feeling uncertain about his thoughts in the area. If so, his sense of unease may have intensified just over a year later, when Richard Waller presented the Royal Society with his edition of Hooke's posthumous works[178]. As well as the treatises on method and light that he had previously mentioned, Waller included Hooke's writings on subjects including comets, earthquakes, navigation and astronomy[179]. Lodged among these documents is a short paper, which he calls 'A Lecture on Light', but which his editorial postscript reveals to be the account of the experiment on diffraction that Hooke had read before the Royal Society back in February 1675[180].

[176] This idea appears in Westfall, *Never at Rest*, 643.
[177] Newton, 'The Fourth Book', 336^{r}. The second draft also concludes with hypothetical comments; see 338^{r-v}.
[178] Waller, ed., *Posthumous Works*. The work was presented on 30 May 1705; see Royal Society MS JBO/11, 72.
[179] Hooke, 'A General Scheme', 'Lectures on Light', 'Of the Nature of Comets', 'Of Earthquakes' and 'Concerning Navigation and Astronomy'.
[180] Hooke, 'A Lecture on Light'. Waller's postscript is Ccc1^{v}.

The publication of Hooke's experiment placed Newton in an awkward position. He may, irrationally, have felt subject to an implicit, posthumous challenge: perhaps the discourse kindled the sense that his treatment of diffraction had been inadequate. Yet, having presented himself as a man who would rather sit on his work than engage in disputes on it, he could hardly respond directly.

A response is, however, visible in the queries appended to subsequent editions of the *Opticks*. The Latin edition of 1706 leaves the original material largely untouched[181], but it adds seven queries, the first two of which discuss the unusual refraction observed by Christiaan Huygens in the mineral now known as 'Iceland spar'[182], with Newton suggesting that the phenomenon may be attributable to the different properties of the 'sides' of a ray of light[183]. The following queries briefly discuss and dismiss hypotheses, such as those expressed by Huygens and Hooke, in which light is understood to function like a wave[184]. Newton then presents his own idea, that it is comprised of corpuscules[185], before concluding with a familiar question: "Have not the small Particles of Bodies certain Powers, Virtues or Forces, by which they act at a distance, not only upon the Rays of Light for reflecting, refracting and inflecting them, but also upon one another for producing a great part of the Phænomena of Nature?"[186].

---

[181] He inserts a discussion of different kinds of flame in question ten; see *Optice*, Oo3^{v}-Oo4^{v}. In the 'Errata, Corrigenda, & Addenda', he adds examples of things that emit light to question eight and evidence for the retention of heat to question eleven; see A4^{r}-b2^{v}, at b2^{r-v}.
[182] Newton, *Optice*, Qq1^{r}-Yy1^{v}, at Qq1^{r}-Qq3^{r} and Qq3^{v}-Qq4^{v}. Huygens and Newton had discussed the phenomenon at a meeting of the Royal Society on 12 June 1689; see Royal Society MS JBO/8, 264-5, at 265. The former published his account the following year in *Traité de la lumière*, F4^{v}-N3^{r}. For an overview of the relationship between the two men's optical work, see Shapiro, 'Huygens's *Traité de la lumière* and Newton's *Opticks*'.
[183] He uses the term 'latera'; see *Optice*, Qq3^{v}. It is translated as 'sides' in *Opticks* (second edition), Y7^{r}.
[184] Newton, *Optice*, Qq4^{v} and Rr1^{r}-Ss1^{r}. For an overview of Huygens's wave theory, see Shapiro, 'Kinematic Optics', 207-44.
[185] Newton, *Optice*, Ss1^{r}-Ss3^{r}.
[186] *Annon exiguæ corporum particulæ certas habent virtutes, potentias, sive vires; quibus, per interjectum aliquod intervallum, agant, non modo in radios Luminis, as eos reflectendos, refringendos,*

If Newton's return to the queries resulted from a sense of unease about his inability to provide a satisfactory account of diffraction, his anxiety may have been exacerbated by the recognition that the issue at the heart of the phenomenon is a fundamental one for the study of nature: how to explain action at a distance.

Indeed, the fundamental nature of the problem is, once more, reflected in the range of material that Newton accumulates. The final query added to the *Optice* in 1706 is largely devoted to chymical matters, of a kind that also appear briefly in the earlier manuscript propositions[187], but it opens with a reference to gravity, magnetism and electricity[188]. The accumulation of evidence, of course, serves to affirm the existence of action at a distance, but it does not go very far towards explaining it. Newton acknowledges the point explicitly: "How these Attractions may be perform'd I do not here consider […] I use that Word here to signify only in general any Force by which Bodies tend towards one another, whatsoever be the Cause"[189].

By the time of the publication of the second English edition, in 1717 (re-issued in 1718), he seems to have had further thoughts. Again, the existing material is left largely untouched[190]; again, however, he adds supplementary queries, this time placing them between the original ones and those included in the Latin translation[191]. In the second

& inflectendos; verum etiam muto in se ipsæ, ad producenda pleraque Phenomena Naturæ, Newton, *Optice*, Ss4^{v}-Yy1^{v}, at Ss4^{v}, translated in *Opticks* (second edition), Z7^{v}.

[187] Newton, 'The Fourth Book', 342^{v} and 338^{r}.

[188] Newton, *Optice*, Ss4^{v}.

[189] *Qua causa efficiente hæ Attractiones peraguntur, in id vero hic non inquiro* […] *Hanc vocem* Attractionis *ita hic accipi velim, ut in universum solummodo vim aliquam significare intelligatur, qua Corpora ad se mutuo tendant; cuicunque demum causæ attribuenda sit illa vis*, Newton, *Optice*, Ss4^{v}, translated in *Opticks* (second edition), Z8^{r}.

[190] Newton adds further things that emit light by motion to question eight; he fleshes out the discussion of vision in question sixteen; and he includes further examples of chemical reactions in question twenty-three (now thirty-one); see *Opticks* (second edition), X6^{r-v}, Y1^{r-v}, and Ss4^{v}-Yy1^{v}.

[191] Newton, *Opticks* (second edition), Y1^{v}-Y4^{v}.

of the new queries, he introduces a medium, which is described as "exceedingly more rare and subtile than the Air, and exceedingly more elastick and active"[192]. As evidence for the existence of this medium, he describes an experiment in which a thermometer is placed in a vacuum, but still registers changes in the ambient temperature[193]. He does not mention the fact, but the experiment in question had been conducted before the Royal Society in November 1716 by the experimentalist and committed Newtonian, John Theophilus Desaguliers[194].

In the following query, Newton suggests that refraction results from the different densities of the medium – which he now calls "this Ætherial Medium" – in different places[195]. In the query after that, he asks: "doth not the gradual condensation of this Medium extend to some distance from the Bodies, and thereby cause the Inflexions of the Rays of Light, which pass by the edges of dense Bodies, at some distance from the Bodies?"[196] Having thus used æther as a means of explaining diffraction, he goes about countering potential objections, doing so with reference to another experiment, this time one that is familiar from the 'Hypothesis' dispatched to the Royal Society back in 1675: "If any one would ask me how a Medium can be so rare, let him tell me […] how an electrick Body can by Friction emit an Exhalation so rare and subtile, and yet so potent […] to be able to agitate and carry up Leaf Copper, or Leaf Gold, at the distance of above a Foot from the electrick Body?"[197]

---

[192] *Ibid.*, Y2[r-v], at Y2[v].
[193] *Ibid.*, Y2[r].
[194] The meeting took place on 15 November; see Royal Society MS JBO/12, 132-3. For a discussion of the experiment, see Guerlac, 'Newton's Optical Æther', 123-5. For an overview of Desaguliers's life and career, see Carpenter, *John Theophilus Desaguliers*.
[195] Newton, *Opticks* (second edition), Y2[v].
[196] *Ibid.*, Y2[v].
[197] *Ibid.*, Y4[r].

An account of the experiment with the thermometer *in vacuo* opens the manuscript draft of these additional queries, which Newton prepared at some point between 1715 and 1717[198]. Later in the manuscript, he leaves a space for an experiment to be copied in, which he remembers having sent to Henry Oldenburg forty years previously: presumably it is that recorded in the 'Hypothesis'[199]. These examples of practical work, with others included alongside them, seem to have temporarily persuaded Newton to alter the structure of the third book of *Opticks*. The material included in the draft is arranged not as a series of queries, but as observations, a "Part II" designed to complement the first part on diffraction, but this time concerned with "the Medium through which light passes, & the Agent which emits it"[200].

In the transition from manuscript to print, however, Newton abandoned the plan: as with the publication of the first edition of the *Opticks* in 1704, he seems to have decided that his thoughts were best expressed as speculative queries. Perhaps he considered the effort involved in restructuring the book and changed his mind. Or perhaps he concluded that the practical work that he had gathered did not, in fact, allow him to proceed as positively as he had hoped. Certainly, when it comes to discussing æther in print, he is notably tentative: in the closest that he comes to a description of the substance, in the second English edition of 1717, he speculates that it "may contain Particles which endeavour to recede from one another [and] are exceedingly smaller than those of Air, or even than those of Light". But, he admits parenthetically: "I do not know what this *Æther* is"[201].

---

198 Newton, 'Observations concerning the Medium through which Light Passes', 623^r. For a discussion of the draft, see Guerlac, 'Newton's Optical Æther'.
199 Newton, 'Observations concerning the Medium through which Light Passes', 626^v and 627^r.
200 *Ibid.*, 623^r
201 Newton, *Opticks* (second edition), Y3^v.

***

Waiting for the death of an adversary is, to put it mildly, an unusual thing to do. From an intellectual perspective, it looks like an admission of failure. Newton failed to explain diffraction. He failed, moreover, to deal satisfactorily with the issue at the heart of the problem: action at a distance. He left his work unpublished until Hooke had departed the scene, but his anxiety hardly seems to have diminished after the latter's death. Indeed, the spectre of Hooke's posthumous judgement can be seen lurking behind the additions to the subsequent editions of *Opticks*.

Viewed from another angle, however, Newton's decision was a triumph. The work stands as one of the pillars on which his posthumous fame rests and its reputation surely owes something to the relative lack of intellectual conflict accompanying its publication. The book proved, in fact, hugely popular with the literate public, as is evident from the appetite for further editions. Its success may, in part, be due to the freewheeling speculations with which the author ends it, but some credit must also go to his painstaking descriptions of experimental activity: it is, after all, no coincidence that, throughout the centuries, the prism has played such a prominent role in Newtonian iconography. Newton's experiments, then, may have been consistently insufficient for Robert Hooke, but they were more than adequate for their audience, the public at large, a fact that in the long run has proved more significant.

Conclusion

What is the past, metaphorically speaking? In the introduction to a book that sets out to explain "how historians think", John Lewis Gaddis invokes "a fog-shrouded landscape in which the fantastic shapes of more distant promontories are only partly visible"[1]. Many historians would, I suspect, recognise the metaphor. And many would, no doubt, consider their work to involve a faithful representation of this landscape, in all its mysterious depth and texture. The word 'landscape', though, is an interesting one, the term referring both to natural scenery and to the artistic depiction of that scenery. Indeed, Gaddis's 'landscape' in the first sense turns out, in fact, to be a 'landscape' in the second: the fog and the promontories that he describes are those represented in Caspar David Friedrich's *Der Wanderer über dem Nebelmeer* (*The Wanderer above the Sea of Fog*), a picture that adorns the front cover of his book (see figure 1). There is, then, some irony at play here: Gaddis conjures a rich, three-dimensional terrain – "mountains off to the left, plains to the right, and perhaps very far away [...] an ocean"[2] – by means of a two-dimensional painting. His introduction creates the strange sense of a shift in dimensions, from three to two. In fact, this dimensional shift is present from the very opening of the book, in the move from the title, *The Landscape of History*, to the sub-title, *How Historians Map the Past*[3].

[1] Gaddis, *The Landscape of History*, x and 1.
[2] *Ibid*., 1.
[3] For some other recent discussions of the business of history, see Cannadine, ed., *What is History Now?*, Evans, *In Defence of History*, Guldi and Armitage, *The History Manifesto*, Jenkins, *On 'What is History?'*, and Rublack, ed., *A Concise Companion to History*. For older, but still worthwhile works, see Bloch, *The Historian's Craft*, and Carr, *What is History?*.

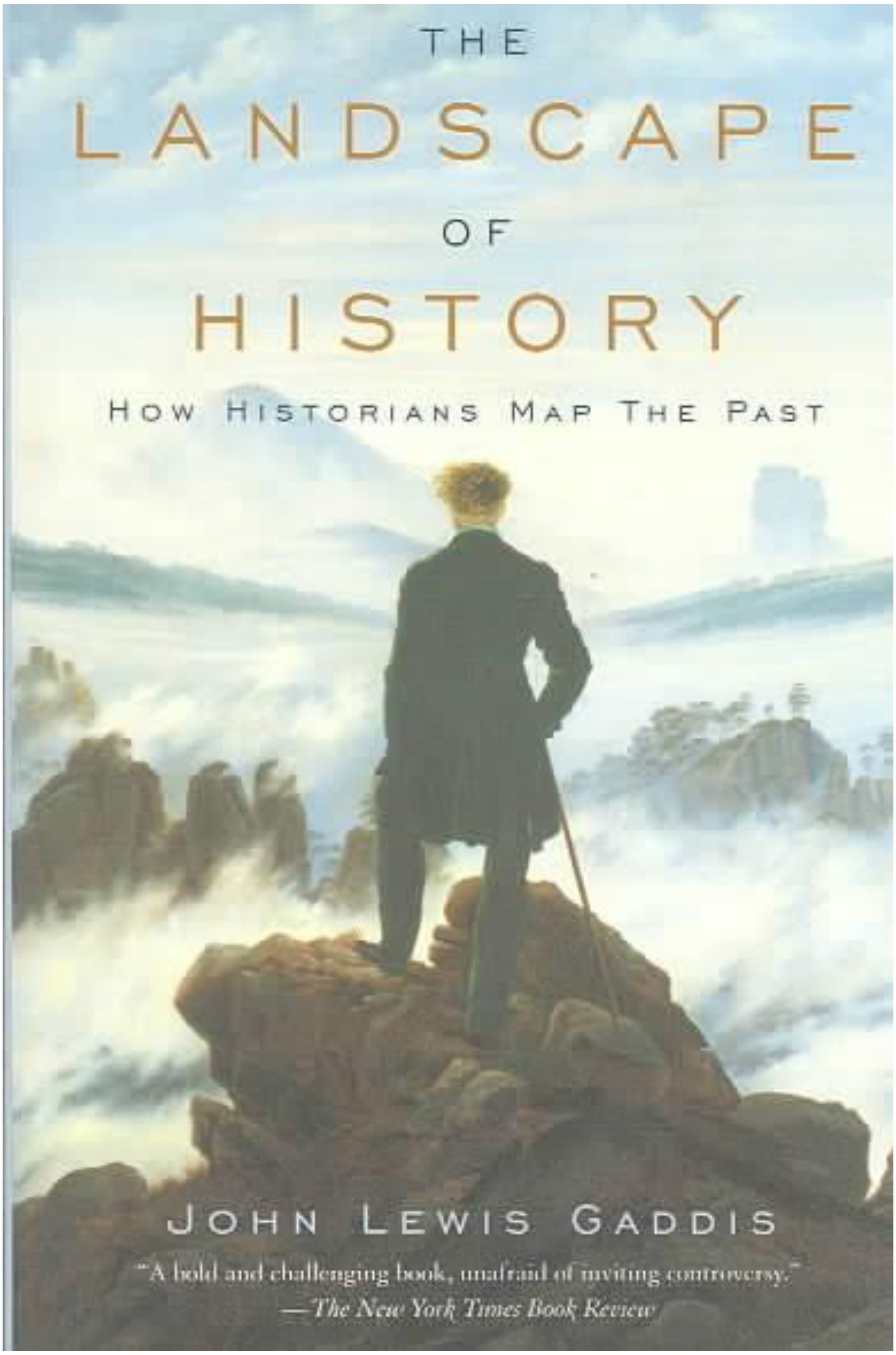


Fig. 1 Front cover of Gaddis, *The Landscape of History*.

John Lewis Gaddis may not have intended to conjure such a strange shift in dimensions, but the shift does, I think, have say something meaningful to say about the experiences of a historian. Our work involves the investigation of a richly textured world and the inability to represent it in all its richness and texture. Like Caspar David Friedrich's wanderer, we survey a dramatic landscape, but, like Friedrich himself, we can only depict it with oil on canvas. Like a wanderer, we move through terrain that is, at times, breath-taking, but, like a cartographer, all we produce is lines on a page. There is, of course, a risk of mixed metaphors here: are we creating a painting or a map? It is a question that different historians would, no doubt, answer in different ways. In both cases, however, the metaphor conveys a sense of loss. When it comes to historical writing, there is always something missing. We cannot capture it all.

The work that features in this thesis is primarily the product of a desire to depict depth. I wanted to highlight the prevalence of instruments and experiments in seventeenth-century optics, but I was especially eager to give an impression of the culture in which this practical activity occurred. I wanted to provide evidence of the fact that it happened, but I was particularly keen to convey a sense of its value. The result is a study comprised of case-studies, an approach that allows me to identify not only the presence of practical work, but also an important reason for conducting it. As I mentioned in my introduction, a number of rhetoricians of science have stressed the idea that scientific work involves persuading an audience. They have, however, sometimes tended to assume that this persuasion simply takes the form of a scientist's deployment of various means to convince an audience that he or she is right about an aspect of the natural world. As I hope is clear from the preceding chapters, my sense is that the practical work evident in seventeenth-century optics also had value as a polemical tool: it could serve to convince an audience that a competitor was wrong.

Alongside depth, I also hoped to convey length. Perhaps conscious of what Jo Guldi and David Armitage have called the "spectre of the short term"[4], I was keen for the thesis to cover an extended period of time. As a result, my four case-studies are drawn from four subsequent generations in the seventeenth century. Likewise, the philosophical works that I discuss range from Francis Bacon's *De principiis atque originibus*, written in or shortly after 1612, to the second edition of Isaac Newton's *Opticks*, published in 1717. My twin goals throughout were to highlight the prevalence of instruments and experiments and to emphasise the value of practical activity in polemical contexts. Covering an extended period of time, however, also allows me to connect my work with a narrative about the increasingly public nature of natural philosophy in this period. In each chapter, practical work reaches a larger audience than is the case in the previous: from Francis Bacon's private record of an experiment conducted in the dark to Isaac Newton's publication of his work with prisms. If, as Steven Shapin and others have suggested, an important strand in the progressively public character of seventeenth-century natural philosophy involves the quest for assent and the desire properly to manage dissent, the activity foregrounded here emphasises the ongoing presence of a disorderly spirit of dispute.

There is, of course, a loss: we cannot capture it all. In my case, the pursuit of depth and length comes at the expense of breadth. Not only is my focus restricted somewhat arbitrarily to England; it is also restricted to the work of four individuals within

[4] Guldi and Armitage, *The History Manifesto*, 1.

England. Each is the major figure active within his generation, but a reader could quite reasonably ask how robust any general conclusions drawn from such a small sample size will be. Are four case-studies enough to declare the prevalence of instruments and experiments within seventeenth-century work on optics? Are four analyses of the background for practical activity enough to state its value in polemical circumstances?

The practice of history is, however, not a lonely pursuit. Unlike Caspar David Friedrich's wanderer, the modern historian is not alone on a rocky promontory, his face toward the wind. (He is also not necessarily a man). As a guide to the vast and dramatic landscape that is seventeenth-century natural philosophy, what I have produced may not be of much benefit for anyone hoping to stray beyond the rather narrow path that I have explored in such depth. Perhaps, however, it is not a map, but a painting. And if this painting manages to convey an impression of the terrain and inspires fellow wanderers in their travels, it will, I hope, not have been painted in vain.

Bibliography

Works are arranged alphabetically by author's surname, then chronologically by date of publication, except in cases where another order seems more natural, e.g. numbered volumes in a collection of works.

Alexander, Amir. 'Lunar Maps and Coastal Outlines: Thomas Harriot's Mapping of the Moon'. *Studies in History and Philosophy of Science* 29, no. 3 (1998): 345-68.

Allen, D. E. 'Merret, Christopher'. In *The Oxford Dictionary for National Biography*. Accessed at www.oxforddnb.com.

Alsbury, Colin. 'Aylesbury, Sir Thomas'. In *The Oxford Dictionary for National Biography*. Accessed at www.oxforddnb.com.

Andrade, E. N. da C. 'Wilkins Lecture: Robert Hooke'. *Proceedings of the Royal Society, Series A: Mathematical, Physical, and Engineering Sciences* 201 (1950): 439-73, also published in *Series B: Biological Sciences* 137 (1950): 153-87

Anonymous. *Horæ subseciuæ. Observations and Discourses*. London, 1620.

Anstey, Peter R. 'Experimental versus Speculative Natural Philosophy'. In *The Science of Nature in the Seventeenth Century: Patterns of Changes in Early Modern Natural Philosophy*, 215-42. Edited by Peter R. Anstey and John A. Schuster. Dordrecht: Springer, 2005.

Aristotle. *Nicomachean Ethics*. In *Aristotelis opera*. 5 vols. Vol. 2, 1094-1181. Edited by Immanuel Bekker, Christian August Brandis and Hermann Bonitz. Berlin: Georg Reimer, 1831-70.

Ash, Eric H. *Power, Knowledge and Expertise in Elizabethan England*. Baltimore: The Johns Hopkins University Press, 2004.

Asimov, Isaac. *Eyes on the Universe: A History of the Telescope*. London: André Deutsch, 1976.

Assenza, Valeria Giachetti. 'Bernardino Telesio: Il migliore dei moderni. I riferimenti a Telesio negli scritti di Francesco Bacone'. *Rivista di storia della filosofia* 35 (1980): 41-78.

Aubrey, John. *Brief Lives, chiefly of Contemporaries, set down by John Aubrey, between the Years 1669 and 1696*. Edited by Andrew Clark. 2 vols. Oxford: Clarendon Press, 1898.

Aubrey, John. *Brief Lives with An Apparatus for the Lives of our English Mathematical Writers*. Edited by Kate Bennett. 2 vols. Oxford: Oxford University Press, 2015.

Bacon, Francis. *De augmentis scientiarum*. In *The Works of Francis Bacon*. 7 vols. Vol. 1, 415-840. Translated in vols. 4 and 5, 273-498 and 3-123. Edited by James

Spedding, Robert Leslie Ellis and Douglas Denon Heath. London: Longman *et al*., 1857-9.

Bacon, Francis. *Sylva sylvarum*. In *The Works of Francis Bacon*. 7 vols. Vol. 2, 331-672. Edited by James Spedding, Robert Leslie Ellis and Douglas Denon Heath. London: Longman *et al*., 1857-9.

Bacon, Francis. *New Atlantis*. In *The Works of Francis Bacon*. 7 vols. Vol. 3, 125-66. Edited by James Spedding, Robert Leslie Ellis and Douglas Denon Heath. London: Longman *et al*., 1857-9.

Bacon, Francis. *Physiological and Medical Remains*. In *The Works of Francis Bacon*. 7 vols. Vol. 3, 799-836. Edited by James Spedding, Robert Leslie Ellis, and Douglas Denon Heath. London: Longman *et al*., 1857-9.

Bacon, Francis. *The Advancement of Learning*. In *The Oxford Francis Bacon 4. The Advancement of Learning*, 3-193. Edited by Michael Kiernan. Oxford: Clarendon Press, 2000.

Bacon, Francis. *De fluxu et refluxu maris*. In *The Oxford Francis Bacon 6. Philosophical Studies c.1611-c.1619*, with a facing-page translation, 63-93. Edited by Graham Rees. Oxford: Clarendon Press, 1996.

Bacon, Francis. *Descriptio globi intellectualis*. In *The Oxford Francis Bacon 6. Philosophical Studies c.1611-c.1619*, with a facing-page translation, 95-169. Edited by Graham Rees. Oxford: Clarendon Press, 1996.

Bacon, Francis. *De principiis atque originibus*. In *The Oxford Francis Bacon 6. Philosophical Studies c.1611-c.1619*, with a facing-page translation, 195-267. Edited by Graham Rees. Oxford: Clarendon Press, 1996.

Bacon, Francis. *Distributio operis*. In *The Oxford Francis Bacon 11. The Instauratio magna Part II: Novum organum and Associated Texts*, with a facing-page translation, 26-47. Edited by Graham Rees with Maria Wakely. Oxford: Clarendon Press, 2004.

Bacon, Francis. *Novum organum*. In *The Oxford Francis Bacon 11. The Instauratio magna Part II: Novum organum and Associated Texts*, with a facing-page translation, 48-447. Edited by Graham Rees with Maria Wakely. Oxford: Clarendon Press, 2004.

Bacon, Francis. *Parasceve, ad historiam naturalem et experimentalem*. In *The Oxford Francis Bacon 11. The Instauratio magna Part II: Novum organum and Associated Texts*, with a facing-page translation, 448-85. Edited by Graham Rees with Maria Wakely. Oxford: Clarendon Press, 2004.

Bacon, Francis. *Historia naturalis et experimentalis, ad condendam philosophiam*. In *The Oxford Francis Bacon 12. The Instauratio magna Part III: Historia naturalis et experimentalis: Historia ventorum and Historia vitæ et mortis*, with a facing-page translation, 6-17. Edited by Graham Rees with Maria Wakely. Oxford: Clarendon Press, 2007.

Bacon, Francis. *Historia ventorum*. In *The Oxford Francis Bacon 12. The Instauratio magna Part III: Historia naturalis et experimentalis: Historia ventorum and Historia vitæ et mortis*, with a facing-page translation, 18-131. Edited by Graham Rees with Maria Wakely. Oxford: Clarendon Press, 2007.

Bacon, Francis. *Aditus ad titulos in proximos quinque menses destinatos*. In *The Oxford Francis Bacon 12. The Instauratio magna Part III: Historia naturalis et experimentalis: Historia ventorum and Historia vitæ et mortis*, with a facing-page translation, 132-9. Edited by Graham Rees with Maria Wakely. Oxford: Clarendon Press, 2007.

Bacon, Francis. *Historia vitæ & mortis*. In *The Oxford Francis Bacon 12. The Instauratio magna Part III: Historia naturalis et experimentalis: Historia ventorum and Historia vitæ et mortis*, with a facing-page translation, 140-377. Edited by Graham Rees with Maria Wakely. Oxford: Clarendon Press, 2007.

Bacon, Francis. *Historia densi & rari*. In *The Oxford Francis Bacon 13. The Instauratio magna: Last Writings*, with facing-page translations, 1-34 and 35-169. Edited by Graham Rees. Oxford: Clarendon Press, 2000.

Bacon, Francis. *Historia & inquisitio de animato & inanimato*. In *The Oxford Francis Bacon 13. The Instauratio magna: Last Writings*, with a facing-page translation, 228-235. Edited by Graham Rees. Oxford: Clarendon Press, 2000.

Bacon, Francis. *Inquisitio de magnete*. In *The Oxford Francis Bacon 13. The Instauratio magna: Last Writings*, with a facing-page translation, 238-241. Edited by Graham Rees. Oxford: Clarendon Press, 2000.

Bacon, Francis. *Topica inquisitionis de luce et lumine*. In *The Oxford Francis Bacon 13. The Instauratio magna: Last Writings*, with a facing-page translation, 244-57. Edited by Graham Rees. Oxford: Clarendon Press, 2000.

Bacon, Francis. *The Essayes or Counsels, Civill and Morall*. In *The Essayes or Counsels, Civill and Morall*, 1-178. Edited by Michael Kiernan. Oxford: Clarendon Press, 1985. Republished in 2000 as *The Oxford Francis Bacon 15*.

Barbour, Reid. *Sir Thomas Browne: A Life*. Oxford: Oxford University Press, 2013.

Barker, John. *Strange Contrarieties: Pascal in England during the Age of Reason*. Montreal: McGill-Queen’s University Press, 1975.

Barnard, Toby. ‘Southwell, Sir Robert’. In *The Oxford Dictionary for National Biography*. Accessed at www.oxforddnb.com.

Barrow, Isaac. *Lectiones XVIII, Cantabrigiæ in scholis publicis habitae*. London, 1669.

Bechler, Zev. ‘Newton’s Disputes of 1672: A Study of the Grammar of Dissent in Science’. In *The Interaction Between Science and Philosophy*, 115-42. Edited by Yehuda Elkana. New York: Humanities Press, 1974.

Bechler, Zev. ‘‘A Less Agreeable Matter’: The Disagreeable Case of Newton and Achromatic Refraction’. *The British Journal for the History of Science* 8, no. 2 (1975): 101-26.

Bedini, Silvio A. ‘Lens Making for Scientific Instrumentation in the Seventeenth Century’. *Applied Optics* 5, no. 5 (1966): 687-94.

de Beer, E.S., ed. *The Diary of John Evelyn*. 6 vols. Oxford: Clarendon Press, 1955.

Beier, Lucinda McCray. ‘Experience and Experiment: Robert Hooke, Illness and Medicine’. In *Robert Hooke: New Studies*, 235-52. Edited by Michael Hunter and Simon Schaffer. Woodbridge, Suffolk: The Boydell Press, 1989.

Ben-Chaim, Michael. *Experimental Philosophy and the Birth of Empirical Science: Boyle, Locke, and Newton*. Aldershot, Hants.: Ashgate, 2004.

Bennett, J.A. ‘Robert Hooke as Mechanic and Natural Philosopher’. *Notes and Records of the Royal Society of London* 35, no. 1 (1980): 33-48.

Bennett, J.A. ‘The Mechanics’ Philosophy and the Mechanical Philosophy’. *History of Science* 24, no. 1 (1986): 1-28.

Bennett, J.A. ‘Hooke’s Instruments for Astronomy and Navigation’. In *Robert Hooke: New Studies*, 21-32. Edited by Michael Hunter and Simon Schaffer. Woodbridge, Suffolk: The Boydell Press, 1989.

Bennett, J.A. ‘Hooke’s Instruments’. In *London’s Leonardo: The Life and Work of Robert Hooke*, 63-104. Edited by J.A. Bennett, Michael Cooper, Michael Hunter and Lisa Jardine. Oxford: Oxford University Press, 2003.

Bennett, J.A. ‘Instruments and Ingenuity’. In *Robert Hooke: Tercentennial Studies*, 65-76. Edited by Michael Cooper and Michael Hunter. Aldershot, Hants: Ashgate, 2006.

Bennett, J.A. ‘Early Modern Mathematical Instruments’. *Isis* 102, no. 4 (2011): 697-705.

Bennett, J.A., Michael Cooper, Michael Hunter and Lisa Jardine, eds., *London’s Leonardo: The Life and Work of Robert Hooke*. Oxford: Oxford University Press, 2003.

Bernhardt, Jean. ‘Hobbes et le mouvement de la lumière’. *Revue d’histoire des sciences* 30, no. 1 (1977): 3-24.

Bernhardt, Jean. ‘La polémique de Hobbes contre la *Dioptrique* de Descartes dans le ‘Tractatus Opticus II’ (1644)’. *Revue internationale de philosophie* 33, no. 129 (1979): 432-42.

Bernhardt, Jean. *Hobbes*. Paris: Presses Universitaires de France, 1989.

Bernhardt, Jean. ‘L’œuvre de Hobbes en optique et en théorie de la vision’. In *Hobbes oggi: Atti del convegno internazionale di studi promosso da Arrigo Pacchi (Milano-*

Locarno 18-21 Maggio 1988), 245-68. Edited by Andrea Napoli. Milan: Franco Angeli, 1990.

Berryman, Sylvia. *The Mechanical Hypothesis in Ancient Greek Natural Philosophy*. Cambridge: Cambridge University Press, 2009.

Birch, Thomas. *The History of the Royal Society of London for Improving of Natural Knowledge, from its first Rise*. 4 vols. Facsimile edition. New York: Johnson Reprint Corporation, 1968.

Blay, Michel. 'Genèse des couleurs et modèles mécaniques dans l'œuvre de Hobbes'. In *Thomas Hobbes: Philosophie première, théorie de la science et politique*, 153-168. Edited by Yves Charles Zarka and Jean Bernhardt. Paris: Presses Universitaires de France, 1990.

Bloch, Marc. *The Historian's Craft.* Translated by Peter Putnam. Manchester: Manchester University Press, 1992. First published as *Apologie pour l'histoire; ou Métier d'historien*. Paris: Armand Colin, 1949.

Borelli, Arianna. 'Thinking with Optical Objects: Glass Spheres, Lenses and Refraction in Giovan Battista della Porta's Optical Writings'. *Journal of Early Modern Studies* 3, no. 1 (2014): 39-61.

Boudon-Millet, Véronique. 'Vision and Vision Disorders: Galen's Physiology of Sight'. In *Blood, Sweat and Tears: The Changing Concepts of Physiology from Antiquity into Early Modern Europe*, 551-67. Edited by Manfred Horstmanshoff, Helen King and Claus Zittell. Leiden: Brill, 2012.

Boyle, Robert. *New Experiments Physico-Mechanicall, Touching the Spring of the Air, and its Effects*. In *The Works of Robert Boyle*. 14 vols. Vol. 1, 141-301. Edited by Michael Hunter and Edward B. Davis. London: Pickering & Chatto, 1999-2000.

Boyle, Robert. *A Defence of the Doctrine Touching the Spring and Weight of the Air*. In *The Works of Robert Boyle*. 14 vols. Vol. 3, 3-107. Edited by Michael Hunter and Edward B. Davis. London: Pickering & Chatto, 1999-2000.

Boyle, Robert. *Experiments and Considerations Touching Colours*. In *The Works of Robert Boyle*. 14 vols. Vol. 4, 3-201. Edited by Michael Hunter and Edward B. Davis. London: Pickering & Chatto, 1999-2000.

Boyle, Robert. *New Experiments and Observations Touching Cold*. In *The Works of Robert Boyle*. 14 vols. Vol. 4, 203-575. Edited by Michael Hunter and Edward B. Davis. London: Pickering & Chatto, 1999-2000.

Boyle, Robert. *A Continuation of New Experiments Physico-Mechanical, Touching the Spring and Weight of the Air, and their Effects*. In *The Works of Robert Boyle*. 14 vols. Vol. 6, 27-163. Edited by Michael Hunter and Edward B. Davis. London: Pickering & Chatto, 1999-2000.

Boyle, Robert. *The Aerial Noctiluca*. In *The Works of Robert Boyle*. 14 vols. Vol. 9, 265-304. Edited by Michael Hunter and Edward B. Davis. London: Pickering & Chatto, 1999-2000.

Brandt, Frithiof. *Thomas Hobbes's Mechanical Conception of Nature*. Translated by Vaughan Maxwell and Annie Fausbøll. London: Hachette, 1928. First published as *Den Mekaniske Naturopfattelse hos Thomas Hobbes*. Copenhagen: Levin & Munksgaard, 1921.

Brewster, David. *Memoirs of the Life, Writings and Discoveries of Sir Isaac Newton*. 2 vols. Edinburgh: Thomas Constable, 1855.

Bryson, Anna. *From Courtesy to Civility: Changing Codes of Conduct in Early Modern England.* Oxford: Clarendon Press, 1998.

Buchwald, Jed Z. 'Descartes's Experimental Journey Past the Prism and Through the Invisible World to the Rainbow'. *Annals of Science* 65, no. 1 (2008): 1-46.

Buchwald, Jed Z., and Mordechai Feingold. *Newton and the Origin of Civilization*. Princeton: Princeton University Press, 2012.

Bunce, Robin. 'Thomas Hobbes's Relationship with Francis Bacon – An Introduction'. *Hobbes Studies* 16 (2003): 41-83.

Bunce, Robin. *Thomas Hobbes*. London, Continuum, 2009.

Burnett, D. Graham. *Descartes and the Hyperbolic Quest: Lens Making Machines and their Significance in the Seventeenth Century*. Philadelphia: American Philosophical Society, 2005.

Cannadine, David, ed. *What is History Now?* Basingstoke: Palgrave Macmillan, 2002.

Campbell, Mary Blaine. *Wonder and Science: Imagining Worlds in Early Modern Europe*. Ithaca: Cornell University Press, 2004.

Cantor, Geoffrey. *Optics after Newton: Theories of Light in Britain and Ireland, 1704-1840.* Manchester: Manchester University Press, 1983.

Carlyle, E. I. 'Cavendish, William, first Duke of Newcastle upon Tyne'. Revised by Timothy Raylor. In *The Oxford Dictionary for National Biography*. Accessed at www.oxforddnb.com.

Carpenter, Audrey T. *John Theophilus Desaguliers: A Natural Philosopher, Engineer and Freemason in Newtonian England*. London: Continuum, 2011.

Carr, E.H. *What is History?* Cambridge: Cambridge University Press, 1961.

Cavendish, Margaret. *Philosophical and Physical Opinions*. London, 1655.

Centore, F.F. *Robert Hooke's Contributions to Mechanics: A Study in Seventeenth-Century Natural Philosophy*. The Hague: Martinus Nijhoff, 1970.

Chapman, Allan. *England's Leonardo: Robert Hooke and the Seventeenth-Century Scientific Revolution*. Bristol: Institute of Physics Publishing, 2005.

Chapman, Allan. 'Gascoigne, William'. In *The Oxford Dictionary for National Biography*. Accessed at www.oxforddnb.com.

Chernaik, Warren. 'Waller, Edmund'. In *The Oxford Dictionary for National Biography*. Accessed at www.oxforddnb.com.

Clark, Stuart. *Vanities of the Eye: Vision in Early Modern European Culture*. Oxford: Oxford University Press, 2007.

Clucas, Stephen. 'The Atomism of the Cavendish Circle: A Reappraisal'. *The Seventeenth Century* 9, no. 2 (1994): 247-73.

Clucas, Stephen. 'Warner, Walter'. In *The Oxford Dictionary for National Biography*. Accessed at www.oxforddnb.com.

Cohen, I. Bernard. 'Some Recollections of Richard Samuel Westfall (1924-1996)'. In *Isaac Newton's Natural Philosophy*, 317-9. Edited by Jed Z. Buchwald and I. Bernard Cohen. Cambridge, MA.: The MIT Press, 2001.

Cohen, L. Jonathan. *An Introduction to the Philosophy of Induction and Probability*. Oxford: Clarendon Press, 1989.

Cook, Alan. *Edmond Halley: Charting the Heavens and the Seas*. Oxford: Clarendon Press, 1998.

Cooper, Michael. *Robert Hooke and the Rebuilding of London*. Thrupp, Glos.: Sutton Publishing, 2003.

Cooper, Michael. 'Hooke's Career'. In *London's Leonardo: The Life and Work of Robert Hooke,* 1-61. Edited by J.A. Bennett, Michael Cooper, Michael Hunter and Lisa Jardine. Oxford: Oxford University Press, 2003.

Cooper, Michael, and Michael Hunter, eds. *Robert Hooke: Tercentennial Studies*. Aldershot, Hants: Ashgate, 2006.

Cooper, Michael, and Michael Hunter, 'Introduction'. In *Robert Hooke: Tercentennial Studies*, xiii-xx. Edited by Michael Cooper and Michael Hunter. Aldershot, Hants: Ashgate, 2006.

Darrigol, Olivier. *A History of Optics from Greek Antiquity to the Nineteenth Century*. Oxford: Oxford University Press, 2012.

Daston, Lorraine, and Katherine Park. *Wonders and the Order of Nature 1150-1750*. New York: Zone Books, 1998.

Daumas, Maurice. *Scientific Instruments of the Seventeenth and Eighteenth Centuries and Their Makers*. London: Batsford, 1972. Edited and translated by Mary Holbrook. First published as *Les Instruments scientifiques aux XVII et XVIII siècles*. Paris: Presses Universitaires de France, 1953

Dear, Peter. 'Introduction'. In *The Literary Structure of Scientific Argument: Historical Studies*, 1-9. Philadelphia: University of Pennsylvania Press, 1991.

Dear, Peter. *Discipline and Experience: The Mathematical Way in the Scientific Revolution*. Chicago: The University of Chicago Press, 1995.

Deckard, Michael Funk, and Péter Losonczi, eds. *Philosophy Begins in Wonder: An Introduction to Early Modern Philosophy, Theology and Science*. Cambridge: James Clarke, 2011.

Deleule, Didier. '*Experientia-Experimentum* ou le mythe du culte de l'expérience chez Francis Bacon'. In *Francis Bacon: Terminologia e fortuna nel XVII secolo*, 59-72. Edited by Marta Fattori. Rome: Ateneo, 1984.

Descartes, René. *Discours de la méthode pour bien conduire sa raison, & chercher la verité dans les sciences. Plus la Dioptrique, les Meteores et la Geometrie qui sont des essais de cete methode*. Leiden, 1637.

Descartes, René. *La Dioptrique*. In *Œuvres de Descartes*. 11 vols. Vol. 6, 79-228. Edited by Charles Adam and Paul Tannery. Paris: J. Vrin, 1897-1913.

Descartes, René. *Les Météores*. In *Œuvres de Descartes*. 11 vols. Vol. 6, 229-366. Edited by Charles Adam and Paul Tannery. Paris: J. Vrin, 1897-1913.

Descartes, René. *Optics*. Partially translated in *The Philosophical Writings of Descartes*, 152-175, by John Cottingham, Robert Stoothoff and Dugald Murdoch. Cambridge. Cambridge University Press, 1985.

Descartes, René. *Optics*. In *Discourse on Method, Optics, Geometry and Meteorology*, 63-173. Translated by Paul J. Olscamp. Revised edition. Indianapolis: Hackett Publishing, 2001.

Dobbs, Betty Jo Teeter. *The Foundations of Newton's Alchemy, or "The Hunting of the Greene Lyon"*. Cambridge: Cambridge University Press, 1975.

Dobbs, Betty Jo Teeter. *The Janus Faces of Genius: The Role of Alchemy in Newton's Thought*. Cambridge: Cambridge University Press, 1991.

Doherty, Meghan C. 'Discovering the 'True Form': Hooke's *Micrographia* and the Visual Vocabulary of Engraved Portraits'. *Notes and Records: The Royal Society Journal of the History of Science* 66, no. 3 (2012): 211-34.

Drake, Ellen Tan. *Restless Genius: Robert Hooke and his Earthly Thoughts*. Oxford: Oxford University Press, 1996.

Ducheyne, Steffen. ‘Newton on Action at a Distance’. *Journal of the History of Philosophy* 52, no. 4 (2014): 675-701.

‘Espinasse, Margaret. *Robert Hooke*. London: William Heinemann, 1956.

Euclid, Στοιχεία. Basel, 1533.

Euclid, Στοιχεία. Edited and translated by Federico Commandino. London, 1620.

Evans, Richard J. *In Defence of History*. London: Granta, 2000. First published in 1997.

Everest, James. ‘Francis Bacon’s Habit of Repeating Himself. Essay-Review of *The Oxford Francis Bacon 1: Early Writings, 1584-1596*’. *Intellectual History Review* 24, no. 2 (2014): 259-62.

Everest, James. ‘Francis Bacon’s Method and the Investigation of Light’. *Intellectual History Review* 25, no. 4 (2015): 391-400.

Fabri, Honoré. ‘De lumine’. In *Dialogi physici*, A1^{r}-F8^{v}. Lyon, 1669.

Fahnestock, Jeanne. *Rhetorical Figures in Science*. Oxford: Oxford University Press, 1999.

Fara, Patricia. *Newton: The Making of Genius*. London: Macmillan, 2002.

Fara, Patricia. ‘Newton Shows the Light: A Commentary on Newton (1672) ‘A letter […] containing his new theory about light and colours’’, *Philosophical Transactions A: Mathematical and Physical Sciences* 373, no. 2039 (2015): http://dx.doi.org/10.1098/rsta.2014.0213.

Feingold, Mordechai. ‘Isaac Barrow: Divine, Scholar, Mathematician’. In *Before Newton: The Life and Times of Isaac Barrow*, 1-104. Edited by Mordechai Feingold. Cambridge: Cambridge University Press, 1990.

Feingold, Mordechai. ‘Robert Hooke: Gentleman of Science’. In *Robert Hooke: Tercentennial Studies*, 203-17. Edited by Michael Cooper and Michael Hunter. Aldershot, Hants: Ashgate, 2006.

Feingold, Mordechai. ‘Payne, Robert’. In *The Oxford Dictionary for National Biography*. Accessed at www.oxforddnb.com.

Feyerabend, Paul. ‘Classical Empiricism’. In *The Methodological Heritage of Newton*, 152-170. Edited by Robert E. Butts and John Whitney Davis. Toronto: University of Toronto Press, 1970.

Figala, Karin. ‘Newton’s Alchemy’. In *The Cambridge Companion to Newton*, 370-86. Edited by I. Bernard Cohen and George E. Smith. Cambridge: Cambridge University Press, 2002.

Fisher, Philip. *Wonder, the Rainbow and the Aesthetics of Rare Experiences*. Cambridge: Harvard University Press, 2003.

Fludd, Robert. *Utriusque cosmi maioris scilicet et minoris metaphysica, physica atque technica historia.* London, 1617.

Force, James E., and Richard H. Popkin, eds. *Essays on the Context, Nature and Influences of Isaac Newton's Theology*. Archives internationales d'histoire des idées, vol. 129. Dordrecht: Kluwer, 1990.

Force, James E., and Richard H. Popkin, eds. *Newton and Religion: Context, Nature and Influence*. Archives internationales d'histoire des idées, vol. 161. Dordrecht: Kluwer, 1999.

Foucault, Michel. *Power / Knowledge: Selected Interviews and Other Writings 1972-1979.* Edited by Colin Gordon and translated by Colin Gordon, Leo Marshall, John Mepham and Kate Soper. Brighton: The Harvester Press, 1980.

Fournier, Marian. *The Fabric of Life: Microscopy in the Seventeenth Century*. Baltimore: The Johns Hopkins University Press, 1996.

de Franco, Luigi. 'La teoria della luce di Bernardino Telesio'. In *Bernardino Telesio e la cultura napoletana*, 53-77. Edited by Giuseppe Galasso. Naples: Guida, 1992.

Frank, Robert G., Jnr. *Harvey and the Oxford Physiologists: A Study of Scientific Ideas*. Berkeley: University of California Press, 1980.

Gaddis, John Lewis. *The Landscape of History: How Historians Map the Past*. Oxford: Oxford University Press, 2002.

Gal, Ofer. *Meanest Foundations and Nobler Superstructures: Hooke, Newton and the "Compounding of the Celestiall Motions of the Planetts"*. Dordrecht: Springer, 2002.

Gal, Ofer, and Raz Chen-Morris. 'Empiricism without the Senses: How the Instrument Replaced the Eye'. In *The Body as Object and Instrument of Knowledge: Embodied Empiricism in Early Modern Science*, 121-47. Dordrecht: Springer, 2010.

Galilei, Galileo. *Sidereus nuncius*. Venice, 1610. Published in facsimile by Archival Facsimiles, 1987. Translated by William R. Shea in *Galileo's Sidereus Nuncius or A Sidereal Message*. Sagamore Beach: Science History Publications, 2009.

Galilei, Galileo. *Discorsi e dimostrazioni matematiche intorno a due nuove scienze attinenti alla meccanica, ed ai movimenti locali*. In *Le opere di Galileo Galilei*. 20 vols. Vol. 8, 39-346. Edited by Antonio Favaro. Florence: G. Barbera, 1890-1909.

Galluzzi, Paolo, and Maurizio Torrini, eds., *Le opere dei discepoli di Galileo Galilei: Carteggio*. 2 vols. Florence: Giunti-Barbèra, 1975-84.

Gaonkar, Dilip Parameshwar. 'The Idea of Rhetoric in the Rhetoric of Science'. In *Rhetorical Hermeneutics: Invention and Interpretation in the Age of Science*, 25-88.

Edited by Alan G. Gross and William M. Keith. New York: State University of New York Press, 1997.

Gemelli, Benedino. *Aspetti dell'atomismo classico nella filosofia di Francis Bacon e nel seicento*. Florence: Leo S. Olschki, 1996.

Georgescu, Laura. 'A New Form of Knowledge: *Experientia Literata*'. *Societate şi politică* 5, no. 2 (2011): 104-20.

Gibson, R.W. *Francis Bacon: A Bibliography of his Works and Baconiana to the Year 1750*. Oxford: Scrivener Press, 1950.

Gibson, R.W. *Francis Bacon: A Bibliography of his Works and Baconiana to the Year 1750: Supplement*. Oxford: Privately printed, 1959.

Giglioni, Guido. 'Mastering the Appetites of Matter: Francis Bacon's *Sylva sylvarum*'. In *The Body as Object and Instrument of Knowledge: Embodied Empiricism in Early Modern Science*, 149-67. Edited by Charles T. Wolfe and Ofer Gal. Dordrecht: Springer, 2010.

Giglioni, Guido. *Francesco Bacone*. Rome: Carocci, 2011.

Giglioni, Guido. 'How Bacon Became Baconian'. In *The Mechanization of Natural Philosophy*, 27-54. Edited by Daniel Garber and Sophie Roux. Dordrecht: Springer, 2013.

Giglioni, Guido. 'Learning to Read Nature: Francis Bacon's Notion of Experiential Literacy (*Experientia literata*)'. *Early Science and Medicine* 18, no. 4-5 (2013): 405-34.

Giglioni, Guido, James A.T. Lancaster, Sorana Corneanu and Dana Jalobeanu, eds. *Francis Bacon on Motion and Power*. Dordrecht: Springer, 2016.

Giudice, Franco. *Luce e visione: Thomas Hobbes e la scienza dell'ottica*. Florence: Leo S. Olschki, 1999.

Giudice, Franco. 'Optics in Hobbes's Natural Philosophy'. In *Hobbes Studies* 29, no. 1 (2016): 86-102.

Goldgar, Anne. *Impolite Learning: Conduct and Community in the Republic of Letters, 1680-1750*. New Haven: Yale University Press, 1995.

Golinski, J.V. 'A Noble Spectacle: Phosphorus and the Public Cultures of Science in the Early Royal Society'. *Isis* 80, no. 1 (1989): 11-39.

Goodwin, Gordon. 'Clarke, Timothy'. Revised by Michael Bevan. In *The Oxford Dictionary for National Biography*. Accessed at www.oxforddnb.com.

Goodwin, Gordon. 'Henshaw, Nathaniel'. Revised by Patrick Wallis. In *The Oxford Dictionary for National Biography*. Accessed at www.oxforddnb.com.

Gouk, Penelope. ‘The Role of Acoustics and Music Theory in the Scientific Work of Robert Hooke’. *Annals of Science* 37, no. 5 (1980): 573-605.

Gouk, Penelope M. ‘Music in Francis Bacon’s Natural Philosophy’. In *Francis Bacon: Terminologia e fortuna nel XVII secolo*, 139-54. Edited by Marta Fattori. Rome: Ateneo, 1984.

Goulding, Robert. ‘Thomas Harriot’s Optics, Between Experiment and Imagination: The Case of Mr Bulkeley’s Glass’. *Archive for History of Exact Sciences* 68, no. 2 (2014): 137-78.

Granada, Miguel Angel. ‘Bacon and Scepticism’. *Nouvelles de la république des lettres* 26 (2006): 379-93.

Grant, Hardy. ‘Hobbes and Mathematics’. In *The Cambridge Companion to Hobbes*, 108-28. Edited by Tom Sorrell. Cambridge: Cambridge University Press, 1996.

Gregory, James. *Optica promota, seu abdita radiorum reflexorum & refractorum mysteria, geometrice enucleata*. London, 1663.

Gross, Alan G. *The Rhetoric of Science*. Harvard: Harvard University Press, 1990.

Guerlac, Henry. ‘Newton’s Optical Æther’. In *Essays and Papers in the History of Modern Science*, 120-30. Edited by Henry Guerlac. Baltimore: The Johns Hopkins University Press, 1977. First published in *Notes and Records: The Royal Society Journal of the History of Science* 22, no. 1-2 (1967): 45-57.

Guldi, Jo, and David Armitage. *The History Manifesto*. Cambridge: Cambridge University Press, 2014.

Habermas, Jürgen. *The Structural Transformation of the Public Sphere*. *An Inquiry into a Category of Bourgeois Society*. Translated by Thomas Burger with the assistance of Frederick Lawrence. Cambridge: The MIT Press, 1989. First published as *Strukturwandel der Öffentlichkeit: Untersuchungen zu einer Kategorie der Bürgerlichen Gesellschaft*. Munich: Luchterhand, 1962.

Hall, A. Rupert. *Hooke’s Micrographia, 1665-1965*. London: The Athlone Press, 1966.

Hall, A. Rupert. ‘Beyond the Fringe: Diffraction as Seen by Grimaldi, Fabri, Hooke and Newton’. *Notes and Records: The Royal Society Journal of the History of Science* 44, no. 1 (1990): 13-23.

Hall A. Rupert. *All Was Light: An Introduction to Newton’s Opticks*. Oxford, Clarendon Press, 1993.

Hall, A. Rupert, and Marie Boas Hall, eds. *The Correspondence of Henry Oldenburg*. 13 vols. Madison: University of Wisconsin Press, 1965-86.

Hall, A. Rupert, and A.D.C. Simpson. ‘An Account of the Royal Society’s Newton Telescope’. *Notes and Records of the Royal Society of London* 50, no. 1 (1996): 1-11.

Hall, Marie Boas. 'Huygens's Scientific Contacts with England'. In *Studies on Christiaan Huygens*, 66-82. Edited by H.J.M. Bos, M.J.S. Rudwick, H.A.M. Snelders and R.P.W. Visser. Lisse: Swets & Zeitlingers, 1980.

Hall, Marie Boas. *Promoting Experimental Learning: Experiment and the Royal Society*. Cambridge: Cambridge University Press, 1991.

Hall, Marie Boas. *Henry Oldenburg: Shaping the Royal Society*. Oxford: Oxford University Press, 2002.

Halliwell, James, ed., *A Collection of Letters Illustrative of the Progress of Science in England from the Reign of Queen Elizabeth to that of Charles the Second.* London: Dawsons of Pall Mall, 1965. First published in 1841.

Hammond, John H. *The Camera Obscura: A Chronicle*. Bristol: Adam Hilger, 1981.

Hamou, Philippe. *La Mutation du visible: Essai sur la portée épistémologique des instruments d'optique au XVII^{e} siècle. Volume 1: Du Sidereus nuncius de Galilée à la Dioptrique cartésienne*. Villeneuve d'Ascq: Presses Universitaires du Septentrion, 1999.

Hamou, Philippe. *La Mutation du visible: Essai sur la portée épistémologique des instruments d'optique au XVII^{e} siècle. Volume 2: Microscopes et telescopes en Angleterre, de Bacon à Hooke*. Villeneuve d'Ascq: Presses Universitaires du Septentrion, 2001.

Harkness, Deborah. *The Jewel House: Elizabethan London and the Scientific Revolution*. New Haven: Yale University Press, 2008.

Harriot, Thomas. *Artis analyticae praxis, ad aequationes algebraïcas novâ, expeditâ, & generali methodo, resoluendas tractatio*. London, 1631.

Harris, Randy. 'Alan Gross and the Rhetoric of Science'. *Perspectives on Science* 17, no. 3 (2009): 346-80.

Harwood, John T. 'Rhetoric and Graphics in *Micrographia'*. In *Robert Hooke: New Studies*, 119-47. Edited by Michael Hunter and Simon Schaffer. Woodbridge, Suffolk: The Boydell Press, 1989.

Hattab, Helen. 'From Mechanics to Mechanism: The *Quæstiones mechanicæ* and Descartes's Physics'. In *The Science of Nature in the Seventeenth Century: Patterns of Change in Early Modern Natural Philosophy*, 99-130. Edited by Peter R. Anstey and John A. Schuster. Dordrecht: Springer, 2005.

van Helden, Albert. *The Invention of the Telescope*. Transactions of the American Philosophical Society 67, part 4. Philadelphia: American Philosophical Society, 1977.

van Helden, Albert. ‘The Birth of the Modern Scientific Instrument, 1550-1700’. In *The Uses of the Science in the Age of Newton*, 49-84. Edited by John G. Burke. Berkeley: University of California Press, 1983.

van Helden, Albert, Sven Dupré, Rob van Gent and Huib Zuidervaart, eds. *The Origins of the Telescope*. Amsterdam: KNAW Press, 2010.

Henry, John. *Knowledge is Power: Francis Bacon and the Method of Science*. Cambridge: Icon Books, 2002.

Henry, John. ‘Ward, Seth’. In *The Oxford Dictionary for National Biography*. Accessed at www.oxforddnb.com.

Hesse, Mary. ‘Francis Bacon’s Philosophy of Science’. In *Essential Articles for the Study of Francis Bacon*, 114-39. Edited by Brian Vickers. London: Sidgwick & Jackson, 1972. First published in 1968. The article was first printed in *A Critical History of Western Philosophy*, 141-52. Edited by D.J. O’Connor. New York: Macmillan, 1964.

Hesse, Mary B. ‘Hooke’s Philosophical Algebra’. *Isis* 57, no. 1 (1966): 67-83.

Heyman, Jacques. ‘Hooke and Bedlam’. In *Robert Hooke: Tercentennial Studies*, 153-64. Edited by Michael Cooper and Michael Hunter. Aldershot, Hants: Ashgate, 2006.

Hobbes, Thomas. *The History of the Grecian War Written by Thucydides*. In *The English Works of Thomas Hobbes*. 11 vols. Vols. 8 and 9. Edited by William Molesworth. London: John Bohn and Longman, Brown, Green, and Longman, 1839-45.

Hobbes, Thomas. *Elementorum philosophiæ sectio secunda de homine*. In *Thomæ Hobbes Malmesburiensis opera philosophica quæ latine scripsit*. 5 vols. Vol. 2, 1-432. Edited by William Molesworth. London: John Bohn and Longman, Brown, Green and Longman, 1839-45.

Hobbes, Thomas. *Tractatus opticus*. In *Thomæ Hobbes Malmesburiensis opera philosophica quæ latine scripsit*. 5 vols. Vol. 5, 217-48. Edited by William Molesworth. London: John Bohn and Longman, Brown, Green and Longman, 1839-45.

Hobbes, Thomas. ‘Objectiones ad Cartesii meditationes de prima philosophia […] una cum responsionibus Cartesii’. In *Thomæ Hobbes Malmesburiensis opera philosophica quæ latine scripsit*. 5 vols. Vol. 5, 249-74. Edited by William Molesworth. London: John Bohn and Longman, Brown, Green and Longman, 1839-45.

Hobbes, Thomas. *The Elements of Law, Natural and Politic*. In *The Elements of Law, Natural and Politic*, 1-190. Edited by Ferdinand Tönnies. London: Simpkin, Marshall, and Co., 1889.

Hobbes, Thomas. ‘Latin Optical Manuscript’. In ‘Thomas Hobbes: *Tractatus Opticus*’. Edited by Franco Alessio. *Rivista critica di storia della filosofia* 18, no. 2 (1963): 147-288.

Hobbes, Thomas. ‘Anti-White’. In *Critique du De mundo de Thomas White*, 103-438. Edited by Jean Jacquot and Harold Whitmore Jones. Paris: J. Vrin, 1973.

Hobbes, Thomas. *De cive*. In *De cive: The Latin Version*, 69-294. Edited by Howard Warrender. Oxford: Clarendon Press, 1983.

Hobbes, Thomas. *De corpore*. In *Thomas Hobbes: De corpore, elementorum philosophiæ sectio prima*, 1-353. Edited by Karl Schuhmann. Paris: J. Vrin, 1999.

Hobbes, Thomas. *A Minute or First Draught of the Optiques*. British Library MS Harley 3360. Accessed via www.bl.uk/manuscripts.

Hooke, Robert. *An Attempt for the Explication of the Phaenomena, Observable in an Experiment Published by the Honourable Robert Boyle, Esq; In the XXXV. Experiment of his Epistolical Discourse touching the Aire.* London, 1661.

Hooke, Robert. *Micrographia: Or Some Physiological Descriptions of Minute Bodies Made By Magnifying Glasses with Observations and Inquiries Thereupon*. London, 1665. Facsimile edition in volume 13 of R.T. Gunther, *Early Science in Oxford*. Oxford: Printed for the Oxford Historical Society *et al*., 1923-45.

Hooke, Robert. *A Description of Helioscopes, and some other Instruments.* London, 1676.

Hooke, Robert. *Lectures de potentia restitutiva, or of Spring*. London, 1678.

Hooke, Robert. ‘A General Scheme, or Idea of the Present State of Natural Philosophy, and how its Defects may be Remedied’. In *The Posthumous Works of Robert Hooke*, B1^{r}-T1^{v}. Edited by Richard Waller. London, 1705.

Hooke, Robert. ‘Lectures on Light’. In *The Posthumous Works of Robert Hooke*, T2^{r}-Pp2^{v}. Edited by Richard Waller. London, 1705.

Hooke, Robert. ‘A Discourse of the Nature of Comets’. In *The Posthumous Works of Robert Hooke*, Qq1^{r}-Ccc1^{v}. Edited by Richard Waller. London, 1705.

Hooke, Robert. ‘A Lecture of Light’. In *The Posthumous Works of Robert Hooke*, Bbb1^{v}-Ccc1^{v}. Edited by Richard Waller. London, 1705.

Hooke, Robert. ‘Lectures and Discourses of Earthquakes’. In *The Posthumous Works of Robert Hooke*, Aaaa1^{r}-Xxxxx1^{v}. Edited by Richard Waller. London, 1705.

Hooke, Robert. ‘Lectures concerning Navigation and Astronomy’. In *The Posthumous Works of Robert Hooke*, Xxxxx1^{v}-Eeeeeee2^{v}. Edited by Richard Waller. London, 1705.

Horstmann, Frank. *Nachträge zu Betrachtungen über Hobbes Optik*. Berlin: Joachim Mackensen, 2006.

Hunter, Matthew C. *Wicked Intelligence: Visual Art and the Science of Experiment in Restoration London*. Chicago: The University of Chicago Press, 2013.

Hunter, Michael. *Science and Society in Restoration England*. Cambridge: Cambridge University Press, 1981.

Hunter, Michael. *The Royal Society and its Fellows, 1660-1700: The Morphology of an Early Scientific Institution*. BSHS Monographs, vol. 4. Second edition. [*s.l.*]: British Society for the History of Science, 1994. First published in 1982.

Hunter, Michael. *Establishing the New Science: The Experience of the Royal Society*. Woodbridge, Suffolk: The Boydell Press, 1989.

Hunter, Michael. 'Hooke the Natural Philosopher'. In *London's Leonardo: The Life and Work of Robert Hooke*, 105-62. Edited by J.A. Bennett, Michael Cooper, Michael Hunter and Lisa Jardine. Oxford: Oxford University Press, 2003.

Hunter, Michael. *Boyle: Between God and Science*. New Haven: Yale University Press, 2009.

Hunter, Michael, Antonio Clericuzio, and Lawrence M. Principe, eds. *The Correspondence of Robert Boyle.* 6 vols. London: Pickering & Chatto, 2001.

Hunter, Michael, and Simon Schaffer. 'Introduction'. In *Robert Hooke: New Studies*, 1-19. Edited by Michael Hunter and Simon Schaffer. Woodbridge, Suffolk: The Boydell Press, 1989.

Hunter, Michael, and Simon Schaffer, eds. In *Robert Hooke: New Studies*, 1-19. Woodbridge, Suffolk: The Boydell Press, 1989.

Huygens, Christiaan. *Traité de la lumière*. Facsimile edition. London: Dawsons, 1966.

Ilardi, Vincent. *Renaissance Vision from Spectacles to Telescopes*. Philadelphia: American Philosophical Society, 2007.

Iliffe, Rob. '"In the Warehouse": Privacy, Property and Priority in the Early Royal Society'. *History of Science* 30, no. 1 (1992): 29-68.

Iliffe, Rob. 'Material Doubts: Hooke, Artisan Culture and the Exchange of Information in 1670s London'. *British Journal of the History of Science* 28, no. 3 (1995): 285-318.

Iliffe, Rob, and Scott Mandelbrote. *The Newton Project*. Accessed at www.newtonproject.sussex.ac.uk.

Inwood, Stephen. *The Man Who Knew Too Much: The Inventive Life of Robert Hooke, 1635-1703*. London: Pan, 2003.

Jack, Jordynn. ‘A Pedagogy of Sight: Microscopic Vision in Robert Hooke’s *Micrographia’*. *Quarterly Journal of Speech* 95, no. 2 (May 2009): 192-209.

Jacquot, Jean. ‘Sir Charles Cavendish and his Learned Friends: A Contribution to the History of Scientific Relations between England and the Continent in the Earlier Part of the Seventeenth Century: 1. Before the Civil War’. *Annals of Science* 8, no. 1 (1952): 13-27.

Jacquot, Jean. ‘Sir Charles Cavendish and his Learned Friends: A Contribution to the History of Scientific Relations between England and the Continent in the Earlier Part of the Seventeenth Century: 2. The Years of Exile’. *Annals of Science* 8, no. 2 (1952), 175-91.

Jacquot, Jean, and Harold Whitmore Jones. ‘Introduction’. In *Critique du De mundo de Thomas White*, 9-102. Paris: J. Vrin, 1973.

Jalobeanu, Dana. ‘The Philosophy of Francis Bacon’s Natural History: A Research Programme’. *Studii de Ştiinţă şi Cultură* 23 (2010): 18-36.

Jalobeanu, Dana. *The Art of Experimental Natural History: Francis Bacon in Context*. Bucharest: Zeta Books, 2015.

Jalobeanu, Dana. ‘Bacon’s Apples: A Case Study in Baconian Experimentation’. In *Francis Bacon on Motion and Power*, 83-113. Edited by Guido Giglioni, James A.T. Lancaster, Sorana Corneanu and Dana Jalobeanu. Dordrecht: Springer, 2016.

Jardine, Lisa. *Francis Bacon, Discovery and the Art of Discourse*. Cambridge: Cambridge University Press, 1974.

Jardine, Lisa. ‘*Experientia literata* or *Novum organum*? The Dilemma of Bacon’s Scientific Method’. In *Francis Bacon’s Legacy of Texts*, 47-67. Edited by William A. Sessions. New York: AMS Press, 1990. First published as ‘*Experientia literata* ou *Novum organum*? Le dilemme de la méthode scientifique de Bacon’. In *Francis Bacon: Science et méthode*, 135-57. Edited by Michel Malherbe and Jean-Marie Pousseur. Paris: J. Vrin, 1985.

Jardine, Lisa. *On a Grander Scale: The Outstanding Career of Sir Christopher Wren*. London: HarperCollins, 2002.

Jardine, Lisa. *The Curious Life of Robert Hooke: The Man Who Measured London*. London: HarperCollins, 2003.

Jardine, Lisa. ‘Hooke the Man: His Diary and his Health’. In *London’s Leonardo: The Life and Work of Robert Hooke*, 163-206. Edited by J.A. Bennett, Michael Cooper, Michael Hunter and Lisa Jardine. Oxford: Oxford University Press, 2003.

Jardine, Lisa. ‘Robert Hooke: A Reputation Restored’. In *Robert Hooke: Tercentennial Studies*, 247-58. Edited by Michael Cooper and Michael Hunter. Aldershot, Hants: Ashgate, 2006.

Jardine, Lisa. ‘Revisiting Rossi on Francis Bacon: Hands-On Science’. In *Advancements of Learning: Essays in Honour of Paolo Rossi*, 59-76. Edited by John L. Heilbron. Florence: Leo S. Olschki, 2007.

Jardine, Lisa, and Alan Stewart. *Hostage to Fortune: The Troubled Life of Francis Bacon.* London: Victor Gollancz, 1998.

Jenkins, Keith. *On ‘What is History?’: From Carr and Elton to Rorty and White*. London: Routledge, 2001. First published in 1995.

Jesseph, Douglas M. ‘Hobbes and the Method of Natural Science’. In *The Cambridge Companion to Hobbes*, 86-107. Edited by Tom Sorrell. Cambridge: Cambridge University Press, 1996.

Johns, Adrian. *The Nature of the Book: Print and Knowledge in the Making*. Chicago: The University of Chicago Press, 1998.

Johns, Adrian. ‘Reading and Experiment in the Early Royal Society’. In *Reading, Society and Politics in Early Modern England*, 244-71. Edited by Kevin Sharpe and Steven N. Zwicker. Cambridge, Cambridge University Press, 2003.

Jones, J.R. *Country and Court: England 1658-1714.* Cambridge: Harvard University Press, 1978.

Kargon, Robert. *Atomism in England from Harriot to Newton*. Oxford: Clarendon Press, 1966.

Keller, A. G. ‘Rooke, Lawrence’. In *The Oxford Dictionary for National Biography*. Accessed at www.oxforddnb.com.

Kent, Paul, and Allan Chapman, eds., *Robert Hooke and the English Renaissance*. Leominster, Herefordshire: Gracewing, 2005.

Keynes, John Maynard. ‘Newton, the Man’. In *Newton Tercentenary Celebrations*, 27-34. Cambridge: Cambridge University Press, 1947.

King, Henry C. *The History of the Telescope*. New York: Dover Publications, 1955.

Klein, Jürgen. ‘Francis Bacon’s *Scientia Operativa*, the Tradition of the Workshops and the Secrets of Nature’. In *Philosophies of Technology: Francis Bacon and his Contemporaries*. 2 vols. Vol. 1, 21-49. Edited by Claus Zittel, Gisela Engel, Romano Nanni and Nicole C. Karafyllis. Intersections: Yearbook for Early Modern Studies 18. Leiden: Brill, 2008.

Lee, Sidney. ‘Cavendish, William, second Earl of Devonshire’. In *The Oxford Dictionary for National Biography*. Accessed at www.oxforddnb.com.

Leijenhorst, Cees. *The Mechanisation of Aristotelianism: The Late Aristotelian Setting of Thomas Hobbes’s Natural Philosophy*. Leiden: Brill, 2002.

Lefèvre, Wolfgang, ed. *Picturing Machines, 1400-1700*. Cambridge, MA.: The MIT Press, 2004.

Leijenhorst, Cees. 'Bernadino Telesio (1509-1588): New Fundamental Principles of Nature'. In *Philosophers of the Renaissance*, 168-180. Edited by Paul Richard Blum. Washington, D.C.: The Catholic University of America Press, 2010.

Lindberg, David C. *Theories of Vision from Al-Kindi to Kepler*. Chicago: University of Chicago Press, 1976.

Lindberg, David C. 'The Genesis of Kepler's Theory of Light: Light Metaphysics from Plotinus to Kepler'. In *Osiris* (second series) 2 (1986): 4-42.

Lux, David, and Harold Cook. 'Closed Circles or Open Networks? Communicating at a Distance During the Scientific Revolution'. *History of Science* 36, no. 2: 179-211.

Maclean, Ian. 'Fludd, Robert'. In *The Oxford Dictionary for National Biography*. Accessed at www.oxforddnb.com.

de Maistre, Joseph. *Examen de la philosophie de Bacon où l'on traite différentes questions de philosophie rationelle*. Lyon: J.B. Pélagaud, 1855. First published in 1836.

de Maistre, Joseph. *An Examination of the Philosophy of Bacon: Wherein Different Questions of Rational Philosophy are Treated*. Translated by Richard A. Lebrun. Montreal: McGill-Queen's University Press, 1998.

Malcolm, Noel. 'Hobbes and the Royal Society'. In *Perspectives on Thomas Hobbes*, 43-66. Edited by G.A.J. Rogers and Alan Ryan. Oxford: Clarendon Press, 1988. Reprinted in *Aspects of Hobbes*, 217-335. Oxford: Clarendon Press, 2004. First published in 2002.

Malcolm, Noel, ed. *The Correspondence of Thomas Hobbes*. 2 vols. Oxford: Clarendon Press, 1994.

Malcolm, Noel. 'Biographical Register'. In *The Correspondence of Thomas Hobbes*. Edited by Noel Malcolm. 2 vols. Vol. 2, 777-919. Oxford: Clarendon Press, 1994.

Malcolm, Noel. 'A Summary Biography of Hobbes'. In *The Cambridge Companion to Hobbes*, 13-44. Edited by Tom Sorrell. Cambridge: Cambridge University Press, 1996. Reprinted in *Aspects of Hobbes*, 1-26. Oxford: Clarendon Press, 2004. First published in 2002.

Malcolm, Noel. *Aspects of Hobbes*. Oxford: Clarendon Press, 2004. First published in 2002.

Malcolm, Noel, 'The Life of John Pell'. In *John Pell (1611-1685) and his Correspondence with Sir Charles Cavendish: The Mental World of an Early Modern Mathematician*, 11-244. Edited by Noel Malcolm and Jacqueline Stedall. Oxford: Oxford University Press, 2005.

Malcolm, Noel, ed., ‘The Pell-Cavendish Correspondence’. In *John Pell (1611-1685) and his Correspondence with Sir Charles Cavendish: The Mental World of an Early Modern Mathematician*, 329-586. Edited by Noel Malcolm and Jacqueline Stedall. Oxford: Oxford University Press, 2005.

Malcolm, Noel. ‘Hobbes, the Latin Optical Manuscript and the Parisian Scribe’. In *Scribes and Transmission in English Manuscripts, 1400-1700*, 210-32. Edited by Peter Beal and A.S.G Edwards. English Manuscript Studies, 1100-1700, vol. 12. London: The British Library, 2005.

Malcolm, Noel. ‘The Title of Hobbes’s Refutation of Thomas White’s *De mundo*’. *Hobbes Studies* 24, no. 2 (2011): 179-88.

Malcolm, Noel. ‘General Introduction’. In *Thomas Hobbes: Leviathan*. 3 vols. Vol. 1, 1-195. Oxford: Clarendon Press, 2012.

Malcolm, Noel. ‘Hobbes, Thomas’. In *The Oxford Dictionary for National Biography*. Accessed at www.oxforddnb.com.

Malet, Antoni. ‘The Power of Images: Mathematics and Metaphysics in Hobbes’s Optics’. *Studies in History and Philosophy of Science* 32, no. 2 (2001): 303-33.

Malherbe, Michel. ‘Bacon’s Method of Science’. In *The Cambridge Companion to Bacon*, 75-98. Edited by Markku Peltonen. Cambridge: Cambridge University Press, 1996.

Mamiani, Maurizio. ‘The Structure of a Scientific Controversy: Hooke versus Newton about Colours’. In *Scientific Controversies: Philosophical and Historical Perspectives*, 143-152. Edited by Peter Machamer, Marcello Pera and Aristides Baltas. Oxford: Oxford University Press, 2000.

Manuel, Frank E. *A Portrait of Isaac Newton*. Cambridge, MA.: The Belknapp Press, 1968.

Manuel, Frank E. *The Religion of Isaac Newton*. Oxford: Clarendon Press, 1973.

Manzo, Silvia. ‘Probability, Certainty and Facts in Francis Bacon’s Natural Histories: A Double Attitude towards Skepticism’. In *Skepticism in the Modern Age: Building on the Work of Richard Popkin*, 123-37. Edited by José R. Maia Neto, Gianni Paganini and John Christian Laursen. Leiden: Brill, 2009.

Marquer, Eric. ‘Ce que sa polémique avec Descartes a modifié dans la pensée de Hobbes: Histoire d’une controverse’. In *Hobbes, Descartes et la métaphysique*, 15-32. Edited by Dominique Weber. Paris: J. Vrin, 2005.

Marr, Alexander. ‘Introduction’. In *Curiosity and Wonder from the Renaissance to the Enlightenment*, 1-20. Edited by R.J.W. Evans and Alexander Marr. Aldershot, Hants.: Ashgate, 2006.

Martensen, Robert L. ‘Croone, William’. In *The Oxford Dictionary for National Biography*. Accessed at www.oxforddnb.com.

Martinich, A.P. *Hobbes: A Biography*. Cambridge: Cambridge University Press, 1999.

McGuire, J.E. and Martin Tamny. ‘Commentary’. In *Certain Philosophical Questions: Newton’s Trinity Notebook*, 1-325. Edited by J.E. McGuire and Martin Tamny. Cambridge: Cambridge University Press, 1983.

McIntyre, G. S. ‘Brouncker, William’. In *The Oxford Dictionary for National Biography*. Accessed at www.oxforddnb.com.

Medina, José. ‘Hobbes’s Geometrical Optics’. In *Hobbes Studies* 29, no. 1 (2016): 39-65.

Mersenne, Marin. *Harmonicorum libri*. Paris, 1636.

Mersenne, Marin. *Livre de l’utilité de l’harmonie & des autres parties des mathematiques*. In *Seconde partie de l’harmonie universale,* separate signatures. Paris, 1637.

Mersenne, Marin. *Cogita physico mathematica*. Paris, 1644.

Mersenne, Marin. *Universæ geometriæ, mixtæque mathematicæ synopsis*. Paris, 1644.

Middleton, W.E. Knowles. *The History of the Barometer*. Baltimore: The Johns Hopkins University Press, 1968. First published in 1964.

Mill, John Stuart. *A System of Logic, Ratiocinative and Inductive*. In *The Collected Works of John Stuart Mill 7: A System of Logic, Ratiocinative and Inductive*, 1-638. Edited by J.M. Robson. Toronto: University of Toronto Press, 1979.

Millington, E.C. ‘Theories of Cohesion in the Seventeenth Century’. *Annals of Science* 5, no. 3 (1945): 253-269.

Mills, A. A. ‘Single-Lens Magnifiers. Part V: Burning Glasses’. *Bulletin of the Scientific Instrument Scoiety* 58 (1998): 28-32.

Mills, A. A. and P. J. Turvey. ‘Newton’s Telescope: An Examination of the Reflecting Telescope Attributed to Sir Isaac Newton in the Possession of the Royal Society’. *Notes and Records of the Royal Society of London* 33, no. 2 (1979): 133-55.

Mintz, Samuel I. *The Hunting of Leviathan: Seventeenth-Century Reactions to the Materialism and Moral Philosophy of Thomas Hobbes*. Cambridge: Cambridge University Press, 1962.

Mulligan, Lotte. ‘Waller, Richard’. In *The Oxford Dictionary for National Biography*. Accessed at www.oxforddnb.com.

Mulsow, Martin. *Frühneuzeitliche Selbsterhaltung: Telesio und die Naturphilosophie der Renaissance*. Tübingen: Max Niemeyer, 1998.

Nakajima, Hideto. 'Robert Hooke as an Astronomer: Hooke's Optical Research and Instruments in their Historical Context'. In *Robert Hooke: Tercentennial Studies*, 49-62. Edited by Michael Cooper and Michael Hunter. Aldershot, Hants: Ashgate, 2006.

Neri, Janice. 'Some Early Drawings by Robert Hooke'. *Archives of Natural History* 32, no. 1 (April 2005): 41-7.

Neri, Janice. *The Insect and the Image: Visualizing Nature in Early Modern Europe, 1500-1700*. Minneapolis: University of Minnesota Press, 2011.

Newman, William R., ed. *The Chymistry of Isaac Newton*. Accessed at www.webapp1.dlib.indiana.edu/newton/.

Newman, William R., and Lawrence M. Principe. 'Alchemy vs. Chemistry: The Etymological Origins of a Historiographical Mistake'. *Early Science and Medicine* 3, no. 1 (1998): 32-65.

Newton, Isaac. 'M^{r}. Isaac Newtons Observations mentioned in his Foregoing Hypothesis'. Royal Society MS RBO/5, 89-124.

Newton, Isaac. 'Fitzwilliam Notebook'. Accessed online via *The Newton Project* at www.newtonproject.sussex.ac.uk.

Newton, Isaac. 'Out of Philosophicall Transactions'. Cambridge University Library MS Add. 3958, 9^{r}-15^{r}. Accessed via *Cambridge Digital Library* at www.cudl.lib.cam.ac.uk.

Newton, Isaac. 'Observations concerning the Inflexions of the Rays of Light in their Passage by the Surfaces of Bodies at a Distance'. Cambridge University Library MS Add. 3970, 79^{r}-90^{r}. Accessed via *Cambridge Digital Library* at www.cudl.lib.cam.ac.uk.

Newton, Isaac. 'The Fourth Book'. Cambridge University Library MS Add. 3970, 342^{r-v}, 341^{r-v}, 337^{r}-338^{v} and 335^{r}-336^{v}. Accessed via *Cambridge Digital Library* at www.cudl.lib.cam.ac.uk.

Newton, Isaac. 'Of y^{e} Coloured Circles twixt Two Contiguous Glasses'. Cambridge University Library MS Add. 3970, 350^{r}-353^{v}. Accessed via *Cambridge Digital Library* at www.cudl.lib.cam.ac.uk.

Newton, Isaac. 'Of the Refraction of Light in its Passage by Bodies'. Cambridge University Library MS Add. 3970, 371^{r}-372^{v}. Accessed via *Cambridge Digital Library* at www.cudl.lib.cam.ac.uk.

Newton, Isaac. 'Observations of Two Blades'. Cambridge University Library MS Add. 3970, 375^{r} and 376^{r-v}. Accessed via *Cambridge Digital Library* at www.cudl.lib.cam.ac.uk.

Newton, Isaac. 'Of the Inflexion of Light'. Cambridge University Library MS Add. 3970, 377^{r}-378^{v} and 328^{r}-329^{r}. Accessed via *Cambridge Digital Library* at www.cudl.lib.cam.ac.uk.

Newton, Isaac. 'Of the Colours of Plated Transparent Substances'. Cambridge University Library MS Add. 3970, 519^{r}-528^{r}. Accessed via *Cambridge Digital Library* at www.cudl.lib.cam.ac.uk.

Newton, Isaac. 'Observations concerning the Medium through which Light Passes, & the Agent which Emits it'. Cambridge University Library MS Add. 3970, 623^{r}, 624^{r}, 626^{r}-627^{r} and 628^{r}-629^{r}. Accessed via *Cambridge Digital Library* at www.cudl.lib.cam.ac.uk.

Newton, Isaac. *Opticks: Or, a Treatise of the Reflexions, Refractions, Inflexions and Colours of Light*. London, 1704.

Newton, Isaac. *Optice: sive de reflexionibus, refractionibus, inflexionibus & coloribus lucis libri tres*. Translated by Samuel Clarke. London, 1706.

Newton, Isaac. *Opticks: Or, a Treatise of the Reflexions, Refractions, Inflexions and Colours of Light*. Second edition. London, 1718.

Newton, Isaac. 'An Hypothesis explaining the Properties of Light'. Letter 146, in *The Correspondence of Isaac Newton*. 7 vols. Vol. 1, 362-89. Edited by H. W. Turnbull, J.F. Scott, A. Rupert Hall and Laura Tilling. Cambridge: Cambridge University Press, 1959-77.

Newton, Isaac. 'Out of M^{r} Hooks Micrographia'. In *Unpublished Scientific Papers of Isaac Newton*, 400-413. Edited by A. Rupert Hall and Marie Boas Hall. Cambridge: Cambridge University Press, 1962.

Newton, Isaac. 'Early Notes on Reflection and Refraction'. In *The Mathematical Papers of Isaac Newton*. 8 vols. Vol. 1, 551-8. Edited by D.T. Whiteside, with M.A. Hoskin. Cambridge: Cambridge University Press, 1967-81.

Newton, Isaac. 'Of Refractions'. In *The Mathematical Papers of Isaac Newton*. 8 vols. Vol. 1, 559-76. Edited by D.T. Whiteside, with M.A. Hoskin. Cambridge: Cambridge University Press, 1967-1981.

Newton, Isaac. 'The Refraction of Light at a Spherical Surface'. In *The Mathematical Papers of Isaac Newton*. 8 vols. Vol. 1, 577-85. Edited by D.T. Whiteside, with M.A. Hoskin. Cambridge: Cambridge University Press, 1967-81.

Newton, Isaac. 'Certain Philosophical Questions'. In *Certain Philosophical Questions: Newton's Trinity Notebook*, 330-465. Edited by J.E. McGuire and Martin Tamny. Cambridge: Cambridge University Press, 1983.

Newton, Isaac. 'Of Colours'. In *Certain Philosophical Questions: Newton's Trinity Notebook*, 466-89. Edited by J.E. McGuire and Martin Tamny. Cambridge: Cambridge University Press, 1983.

Oster, Malcolm. ‘Goddard, Jonathan’. In *The Oxford Dictionary for National Biography*. Accessed at www.oxforddnb.com.

Pacchi, Arrigo. *Introduzione a Hobbes*. Bari: Laterza, 2009. First published in 1971.

Park, David. *The Fire Within the Eye: A Historical Essay on the Nature and Meaning of Light*. Princeton: Princeton University Press, 1997.

Parry, Richard. ‘*Episteme* and *Techne*’. In *The Stanford Encyclopedia of Philosophy*. Edited by Edward N. Zalta. Autumn 2014. Accessed online at http://plato.stanford.edu/archives/fall2014/entries/episteme-techne.

Pastorino, Cesare. ‘Weighing Experience: Experimental Histories and Francis Bacon’s Quantitative Program’. *Early Science and Medicine* 16, no. 6 (2011): 542-70.

Patrizi, Franceso. *Nova de universis philosophia*. Ferrara, 1591.

Pera, Marcello, and William R. Shea. ‘Preface’. In *Persuading Science: The Art of Scientific Rhetoric*, vii-ix. Canton, MA.: Science History Publications, 1991.

Pérez-Ramos, Antonio, *Francis Bacon’s Idea of Science and the Maker’s Knowledge Tradition*. Oxford: Clarendon Press, 1988.

Poole, Will, Felicity Henderson, and Yelda Nasifoglu, eds. *Hooke’s Books*. Accessed online at http://www.hookesbooks.com.

Popkin, Richard H. *The History of Scepticism from Savonarola to Bayle.* Oxford: Oxford University Press, 2003.

Popper, Karl. *The Logic of Scientific Discovery*. Second edition. London: Hutchinson, 1968. First published in English in 1959; translated by the author from *Logik der Forschung.* Vienna: Springer, 1935.

Popper, Karl. *Conjectures and Refutations: The Growth of Scientific Knowledge*. Revised edition. London: Routledge, 1996. First published in 1963.

Pousseur, Jean-Marie. ‘Bacon, a Critic of Telesio’. In *Francis Bacon’s Legacy of Texts*, 105-17. Edited by William A. Sessions. New York: AMS Press, 1990.

Priestley, Joseph. *The History and Present State of Electricity, with Original Experiments*. London, 1767

Priestley, Joseph. *The History and Present State of Discoveries Relating to Vision, Light, and Colours*. London, 1772.

Prins, Jan. ‘Kepler, Hobbes and Medieval Optics’. *Philosophia naturalis* 24, no. 3 (1987): 287-310.

Prins, Jan. ‘Hobbes on Light and Vision’. In *The Cambridge Companion to Hobbes*, 129-56. Edited by Tom Sorrell. Cambridge: Cambridge University Press, 1996.

Pumfrey, Stephen. ‘Ideas above his Station: A Social Study of Hooke’s Curatorship of Experiments’. *History of Science* 29 (1991): 1-44.

Pumfrey, Stephen. ‘Harriot’s Maps of the Moon: New Interpretations’. *Notes and Records of the Royal Society of London* 63, no. 2 (2009): 163-8.

Pumfrey, Stephen, and Frances Dawbarn. ‘Science and Patronage in England, 1570-1625: A Preliminary Study’. *History of Science* 42, no. 2 (2004): 137-88.

Purver, Margery. *The Royal Society: Concept and Creation.* London: Routledge and Kegan Paul, 1967.

de Quehen, Hugo. ‘Pearson, John’. In *The Oxford Dictionary for National Biography*. Accessed at www.oxforddnb.com.

Rawley, William. *The Life of Francis Bacon*. In *The Works of Francis Bacon*. 7 vols. Vol. 1, 1-18. Edited by James Spedding, Robert Leslie Ellis and Douglas Denon Heath. London: Longman *et al*., 1857-9.

Raylor, Timothy. ‘Newcastle’s Ghosts: Robert Payne, Ben Jonson and the ‘Cavendish Circle’’. In *Literary Circles and Cultural Communities in Renaissance England*, 92-114. Edited by Claude J. Summers and Ted-Larry Pebworth. Columbia: University of Missouri Press, 2000.

Raylor, Timothy. ‘The Date and Script of Hobbes’s Latin Optical Manuscript’. In *Scribes and Transmission in English Manuscripts 1400-1700*, 201-9. Edited by Peter Beal and A.S.G Edwards. English Manuscript Studies, 1100-1700, vol. 12. London: The British Library, 2005.

Rees, Graham. ‘Francis Bacon’s Semi-Paracelsian Cosmology’. *Ambix* 22, no. 2 (1975): 81-101.

Rees, Graham. ‘Francis Bacon’s Semi-Paracelsian Cosmology and the Great Instauration’. *Ambix* 22, no. 3 (1975): 161-73.

Rees, Graham. ‘The Fate of Bacon’s Cosmology in the Seventeenth Century’. *Ambix* 24, no. 1 (1977): 27-38.

Rees, Graham. ‘Matter Theory: A Unifying Factor in Bacon’s Natural Philosophy?’ *Ambix* 24, no. 2 (1977): 110-25.

Rees, Graham. ‘Francis Bacon on Verticity and the Bowels of the Earth’. *Ambix* 26, no. 3 (1979): 202-11.

Rees, Graham. ‘Atomism and ‘Subtlety’ in Francis Bacon’s Philosophy’. *Annals of Science* 37, no. 5 (1980): 549-71.

Rees, Graham. ‘An Unpublished Manuscript by Francis Bacon: *Sylva sylvarum* Drafts and Other Working Notes’. *Annals of Science* 38, no. 4 (1981): 377-412.

Rees, Graham. 'Francis Bacon and *spiritus vitalis*'. In *Spiritus: IVe colloquio internazionale del lessico intellettuale europeo,* 265-81. Edited by Marta Fattori and Massimo Bianchi. Rome: Ateneo, 1984.

Rees, Graham. 'Francis Bacon's Biological Ideas: A New Manuscript Source'. In *Occult and Scientific Mentalities in the Renaissance,* 297-314. Edited by Brian Vickers. Cambridge: Cambridge University Press, 1984.

Rees, Graham. 'Introduction'. In *The Oxford Francis Bacon 6. Philosophical Studies c.1611-c.1619*, xvii-cxvi. Oxford: Clarendon Press, 1996.

Rees, Graham. 'Commentary on *Descriptio globi intellectualis*'. In *The Oxford Francis Bacon 6. Philosophical Studies c.1611-c.1619,* 376-82. Oxford: Clarendon Press, 1996.

Rees, Graham. 'Commentary on *De fluxu et refluxu maris*'. In *The Oxford Francis Bacon 6. Philosophical Studies c.1611-c.1619,* 383-405. Oxford: Clarendon Press, 1996.

Rees, Graham. 'Commentary on *De principiis atque originibus*'. In *The Oxford Francis Bacon 6. Philosophical Studies c.1611-c.1619,* 416-36. Oxford: Clarendon Press, 1996.

Rees, Graham. 'Introduction'. In *The Oxford Francis Bacon 11. The Instauratio magna Part II: Novum organum and Associated Texts*, xix-cxxviii. Oxford: Clarendon Press, 2004.

Rees, Graham. 'Introduction'. In *The Oxford Francis Bacon 12. The Instauratio magna Part III: Historia naturalis et experimentalis: Historia ventorum and Historia vitæ et mortis*, xvii-lxxxviii. Oxford: Clarendon Press, 2007.

Rees, Graham. 'Introduction'. In *The Oxford Francis Bacon 13. The Instauratio magna: Last Writings*, xix-xcvi. Oxford: Clarendon Press, 2000.

Rees, Graham. 'Commentary on *Topica inquisitionis de luce et lumine*'. In *The Oxford Francis Bacon 13. The Instauratio magna: Last Writings*, 332-6. Oxford: Clarendon Press, 2000.

Reeves, Eileen. *Galileo's Glassworks: The Telescope and the Mirror*. Cambridge, MA.: Harvard University Press, 2008.

Reik, Miriam M. *The Golden Lands of Thomas Hobbes*. Detroit: Wayne State University Press, 1977.

Reynolds, Noel, and Arlene Saxonhouse. 'Hobbes and the *Horæ Subsecivæ*'. In *Three Discourses: A Critical Modern Edition of Newly Identified Work of the Young Hobbes*, 3-19. Edited by Noel Reynolds and Arlene Saxonhouse. Chicago: The University of Chicago Press, 1995.

von Rheita, Anton Maria Schyrleus. *Oculus Enoch et Eliæ sive radius sidereomysticus*. Antwerp, 1645.

Richards, Jennifer. *Rhetoric and Courtliness in Early Modern Literature*. Cambridge: Cambridge University Press, 2003.

Riskin, Jessica. *The Restless Clock: A History of the Centuries-Long Argument over What Makes Living Things Tick*. Chicago: The University of Chicago Press, 2016.

Robinson, Henry W., and Walter Adams. *The Diary of Robert Hooke*. London: Taylor & Francis, 1935.

Rogow, Arnold A. *Thomas Hobbes: Radical in the Service of Reaction*. New York: W.W. Norton, 1986.

Ronchi, Vasco. *The Nature of Light: An Historical Survey*. London: Heinemann, 1970. First published in Italian as *Storia della Luce* in 1939.

Rose, Paul Lawrence, and Stillman Drake. 'The Pseudo-Aristotelian *Questions of Mechanics* in Renaissance Culture'. Studies in the Renaissance 18 (1971): 65-104.

Rossi, Paolo. *Francis Bacon: From Magic to Science*. London: Routledge and Kegan Paul, 1968. Translated by Sacha Rabinovitch. First published as *Francesco Bacone: Dalla magia alla scienza*. Bari: Laterza, 1957.

Rossi, Paolo. *Philosophy, Technology and the Arts in the Early Modern Era*. Translated by Salvator Attanasio and edited by Benjamin Nelson. London: Harper & Row, 1970. First published as *I filosofi e le macchine*. Milano: Giangiacomo Feltrinelli, 1962.

Rossi, Paolo. 'Bacon's Idea of Science'. In *The Cambridge Companion to Bacon*, 25-46. Edited by Markku Peltonen. Cambridge: Cambridge University Press, 1996.

Rublack, Ulinka, ed. *A Concise Companion to History*. Oxford: Oxford University Press, 2011.

Ruestow, Edward G. *The Microscope in the Dutch Republic: The Shaping of Discovery*. Cambridge: Cambridge University Press, 1996.

Rusu, Doina-Cristina. 'From Natural History to Natural Magic: Francis Bacon's *Sylva sylvarum*'. Unpublished PhD dissertation. Radboud University, 2013.

Rusu, Doina-Christu, and Christoph Lüthy. 'Extracts from a Paper Laboratory: The Nature of Francis Bacon's *Sylva sylvarum*'. *Intellectual History Review* 27, no. 2 (2017): 171-202.

Sabra, A.I. *Theories of Light from Descartes to Newton*. London: Oldbourne, 1967.

Schaffer, Simon. 'Glass Works: Newton's Prisms and the Uses of Experiment'. In *The Uses of Experiment: Studies in the Natural Sciences*, 67-104. Edited by David Gooding, Trevor Pinch and Simon Schaffer. Cambridge: Cambridge University Press, 1989.

Schickore, Jutta. 'Scientific Discovery'. In *The Stanford Encyclopedia of Philosophy*. Edited by Edward N. Zalta. Spring 2014. Accessed online at http://plato.stanford.edu/entries/scientific-discovery.

Schofield, Robert E. *The Enlightenment of Joseph Priestley: A Study of his Life and Work from 1733 to 1773*. University Park: The Pennsylvania State University Press, 1997.

Schuhmann, Karl. 'Le Concept de l'espace chez Telesio'. In *Bernardino Telesio e la cultura napoletana*, 141-67. Edited by Raffaele Sirri and Maurizio Torrini. Naples: Guida, 1992.

Schuhmann, Karl. 'Hobbes dans les publications de Mersenne en 1644'. *Bulletin Hobbes VII*, 2-7. In *Archives de philosophie* 58, no. 2 (1995).

Scriba, Christoph J. 'Collins, John'. In *The Oxford Dictionary for National Biography*. Accessed at http://www.oxforddnb.com.

Serjeantson, R.W. 'Proof and Persuasion'. In *The Cambridge History of Science. Volume 3: Early Modern Science*, 132-75. Edited by Katherine Park and Lorraine Daston. General editors David C. Lindberg and Ronald L. Numbers. Cambridge: Cambridge University Press, 2006.

Shapin, Steven. 'Pump and Circumstance: Robert Boyle's Literary Technology'. *Social Studies of Science* 14, no. 4 (1984): 481-520. Reprinted in *Never Pure: Historical Studies of Science as if It Was Produced by People with Bodies, Situated in Time, Space, Culture, and Society, and Struggling for Credibility and Authority*, 89-116. Baltimore: Johns Hopkins University Press, 2010.

Shapin, Steven. 'Who Was Robert Hooke?'. In *Robert Hooke: New Studies*, 253-86. Edited by Michael Hunter and Simon Schaffer. Woodbridge, Suffolk: The Boydell Press, 1989.

Shapin, Steven. *A Social History of Truth: Civility and Science in Seventeenth-Century England*. Chicago: University of Chicago Press, 1994.

Shapin, Steven, and Simon Schaffer. *Leviathan and the Air-Pump: Hobbes, Boyle and the Experimental Life*. Princeton: Princeton University Press, 2011. First published in 1985.

Shapiro, Alan E. 'Kinematic Optics: A Study of the Wave Theory of Light in the Seventeenth Century'. *Archive for History of Exact Sciences* 11, no. 2-3 (1973): 134-266.

Shapiro, Alan E., 'Introduction'. In *The Optical Papers of Isaac Newton. Volume I: The Optical Lectures 1670-1672*, 1-25. Edited by Alan E. Shapiro. Cambridge: Cambridge University Press, 1984.

Shapiro, Alan E. 'Huygens's *Traité de la lumière* and Newton's *Opticks*: Pursuing and Eschewing Hypotheses'. *Notes and Records: The Royal Society Journal of the History of Science* 43, no. 2 (1989): 223-47.

Shapiro, Alan E. 'The *Optical Lectures* and the Foundations of the Theory of Optical Imagery'. In *Before Newton: The Life and Times of Isaac Barrow*, 105-178. Edited by Mordechai Feingold. Cambridge: Cambridge University Press, 1990.

Shapiro, Alan E. 'Beyond the Dating Game: Watermark Clusters and the Composition of Newton's *Opticks*'. In *The Investigation of Difficult Things: Essays on Newton and the History of the Exact Sciences in Honour of D.T. Whiteside*, 181-227. Edited by P.M. Harman and Alan E. Shapiro. Cambridge: Cambridge University Press, 1992.

Shapiro, Alan E. *Fits, Passions and Paroxysms: Physics, Method and Chemistry, and Newton's Theories of Coloured Bodies and Fits of Easy Reflection*. Cambridge: Cambridge University Press, 1993.

Shapiro, Alan E. 'Newton's Experiments on Diffraction and the Delayed Publication of the *Opticks*'. In *Isaac Newton's Natural Philosophy*, 47-76. Edited by Jed Z. Buchwald and I. Bernard Cohen. Cambridge, MA.: The MIT Press, 2001.

Shapiro, Alan E. 'Newton's Optics and Atomism'. In *The Cambridge Companion to Newton*, 227-55. Edited by I. Bernard Cohen and George E. Smith. Cambridge: Cambridge University Press, 2002.

Shapiro, Alan E. 'Twenty-Nine Years in the Making: Newton's *Opticks*'. *Perspectives on Science* 16, no. 4 (2008): 417-38.

Shea, William R. *Designing Experiments and Games of Chance: The Unconventional Science of Blaise Pascal*. Canton, MA.: Science History Publications, 2003.

Simpson, A.D.C. 'Robert Hooke and Practical Optics: Technical Support at a Scientific Frontier'. In *Robert Hooke: New Studies*, 33-61. Edited by Michael Hunter and Simon Schaffer. Woodbridge, Suffolk: The Boydell Press, 1989.

Simpson, A. D. C. 'Neile, Sir Paul'. In *The Oxford Dictionary for National Biography*. Accessed at http://www.oxforddnb.com.

Simpson, A.D.C. 'Reeve, Richard'. In *The Oxford Dictionary for National Biography*. Accessed at www.oxforddnb.com.

Skinner, Quentin. 'Retrospect: Studying Rhetoric and Conceptual Change'. In *Visions of Politics. Vol. 1: Regarding Method*, 175-87. Cambridge: Cambridge University Press, 2002.

Smith, A. Mark. *From Sight to Light: The Passage from Ancient to Modern Optics*. Chicago: The University of Chicago Press, 2014.

Sommerville, Johann. 'Lofty Science and Local Politics'. In *The Cambridge Companion to Hobbes*, 245-73. Edited by Tom Sorrell. Cambridge: Cambridge University Press, 1996.

Sorrell, Tom. 'Introduction'. In *The Cambridge Companion to Hobbes*, 1-12. Edited by Tom Sorrell. Cambridge: Cambridge University Press, 1996.

Spedding, James, ed. *The Letters and the Life of Francis Bacon*. 7 vols. London: Longman, Green, Longman and Roberts, and Longmans, Green, Reader and Dyer, 1862-74.

Sprat, Thomas. *The History of the Royal-Society of London, for the Improving of Natural Knowledge.* London, 1667.

Stevenson, David. 'Introduction: The Life of Sir Robert Moray'. In *Letters of Sir Robert Moray to the Earl of Kincardine, 1657-73*, 1-59. Aldershot, Hants.: Ashgate, 2007.

Stewart, Alan. 'Rawley, William'. In *The Oxford Dictionary for National Biography*. Accessed at www.oxforddnb.com.

Stoesser, Alison. 'Robert Hooke's Montagu House: London Architecture with Continental Flair'. In *Robert Hooke: Tercentennial Studies*, 165-79. Edited by Michael Cooper and Michael Hunter. Aldershot, Hants: Ashgate, 2006.

van Strien, Kees. 'Browne, Edward'. In *The Oxford Dictionary for National Biography*. Accessed at http://www.oxforddnb.com.

Stroud, Elaine C. 'Thomas Hobbes's *A Minute or First Draught of the Optiques*: A Critical Edition'. Unpublished PhD dissertation. University of Wisconsin-Madison, 1983.

Stroud, Elaine C. 'Light and Vision: Two Complementary Aspects of Optics in Hobbes's Unpublished Manuscript, *A Minute or First Draught of the Optiques*'. In *Hobbes oggi: Atti del convegno internazionale di studi promosso da Arrigo Pacchi (Milano-Locarno 18-21 Maggio 1988)*, 269-77. Milan: Franco Angeli, 1990.

Stuewer, Roger H. 'A Critical Analysis of Newton's Work on Diffraction'. *Isis* 61, no. 2 (1970): 188-205.

Tanner, Rosalind C.H. 'Thomas Harriot as Mathematician: A Legacy of Hearsay'. *Physis: Rivista Internazionale di Storia della Scienza* 9, nos. 2 and 3 (1967): 235-47 and 257-92.

Telesio, Bernardino. *De rerum natura iuxta propria principia*. 3 vols. Edited by Luigi de Franco, with a facing-page Italian translation. Cosenza; Florence: Casa del Libro; La Nuova Italia, 1965-76.

Tuck, Richard. 'Hobbes and Descartes'. In *Perspectives on Thomas Hobbes*, 11-41. Edited by G.A.J. Rogers and Alan Ryan. Oxford: Clarendon Press, 1988.

Turnbull, H.W., J.F. Scott, A. Rupert Hall and Laura Tilling, eds., *The Correspondence of Isaac Newton*. 7 vols. Cambridge: Cambridge University Press, 1959-77.

Vanagt, Katrien. 'Early Modern Medical Thinking on Vision and the Camera Obscura, V.F. Plempius's *Opthalmographia*'. In *Blood, Sweat and Tears: The Changing Concepts of Physiology from Antiquity into Early Modern Europe*, 569-93. Edited by Manfred Horstmanshoff, Helen King and Claus Zittell. Leiden: Brill, 2012.

Walker, D.P. 'Spirits in Francis Bacon'. In *Francis Bacon: Terminologia e fortuna nel XVII secolo*, 315-27. Edited by Marta Fattori. Rome: Edizioni dell'Ateneo, 1984.

Waller, Richard, ed. *The Posthumous Works of Robert Hooke*. London, 1705.

Warner, Walter. *De loco imaginis*. British Library MS Harl. 6756, 5^{r}-26^{r}.

Warrender, Howard. 'Introduction'. In *De cive: The Latin Version*, 1-67. Oxford: Clarendon Press, 1983.

Weeks, Sophie. 'Francis Bacon's Science of Magic'. Unpublished PhD dissertation. University of Leeds, 2007.

Weeks, Sophie. 'The Role of Mechanics in Francis Bacon's Great Instauration'. In *Philosophies of Technology: Francis Bacon and his Contemporaries*. 2 vols. Vol. 1, 133-95. Edited by Claus Zittel, Gisela Engel, Romano Nanni and Nicole C. Karafyllis. Intersections: Yearbook for Early Modern Studies 18. Leiden: Brill, 2008.

Westfall, Richard S. 'Newton's Reply to Hooke and the Theory of Colours'. *Isis* 54, no. 1 (1963): 82-96.

Westfall, Richard S. *Never at Rest: A Biography of Isaac Newton*. Cambridge: Cambridge University Press, 1980.

Westfall, Richard S. 'Robert Hooke, Mechanical Technology and Scientific Investigation'. In *The Uses of Science in the Age of Newton*, 85-110. Edited by John G. Burke. Berkeley: University of California Press, 1983.

Whitaker, Virgil K. 'Francesco Patrizi and Francis Bacon'. In *Francis Bacon's Legacy of Texts*, 89-104. Edited by William A. Sessions. New York: AMS Press, 1990. First published in *Studies in the Literary Imagination* 4, no. 1 (1971): 107-20.

White, Thomas. *De mundo dialogi tres*. Paris, 1642.

Wilkins, John. *A Discourse Concerning a New World & Another Planet in 2 Bookes*. London, 1640.

Willach, Rolf. *The Long Route to the Invention of the Telescope*. Transactions of the American Philosophical Society 98, part 5. Philadelphia: American Philosophical Society, 2008.

Wilson, Catherine. *The Invisible World: Early Modern Philosophy and the Invention of the Microscope*. Princeton: Princeton University Press, 1995.

Woodland, Patrick. 'Beale, John'. In *The Oxford Dictionary for National Biography*. Accessed at www.oxforddnb.com.

Wolfe, Jessica. *Humanism, Machinery, and Renaissance Literature*. Cambridge: Cambridge University Press, 2009.

Zagorin, Perez. *Francis Bacon*. Princeton: Princeton University Press, 1998.

Zaret, David. 'Religion, Science and Printing in the Public Spheres in Seventeenth-Century England'. In *Habermas and the Public Sphere*, 212-35. Edited by Craig Calhoun. Cambridge: The MIT Press, 1992.

Zarka, Yves Charles. 'La matière et la representation: Hobbes lecteur de la *Dioptrique* de Descartes'. In *Problématique et reception du Discours de la Méthode et des Essais*, 81-98. Edited by Henri Méchoulan. Paris: J. Vrin, 1988.

Ziggelaar, August. *Le physicien Ignace Gaston Pardies S.J. (1636-1673)*. Acta Historica Scientiarum Naturalium et Medicinalium, vol. 26. Odense: Odense University Press, 1971.