



CRAFTING THE MICROWORLD: HOW ROBERT HOOKE CONSTRUCTED KNOWLEDGE ABOUT SMALL THINGS

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This paper investigates the way in which Robert Hooke constructed his microscopical observations. His *Micrographia* is justifiably famous for its detailed engravings, which communicated Hooke's observations of tiny nature to his readers, but less attention has been paid to how he went about making the observations themselves. In this paper I explore the relationship between the materiality of his instrument and the epistemic images he produced. Behind the pictures lies an array of hidden materials, and the craft knowledge it took to manipulate them. By investigating the often counter-theoretical and conflicting practices of his ingenious microscope use, I demonstrate the way in which Hooke crafted the microworld for his readers, giving insight into how early modern microscopy was understood by its practitioners and audience.

Keywords: Robert Hooke; microscope; ingenuity; *Micrographia*

INTRODUCTION

Robert Hooke's *Micrographia* (1665) is a book as much about the relationship between eyesight and knowledge as it is about the particular seeds and moss and fleas that adorn its pages. In it, Hooke tells us that only by adding to our senses with artificial instruments such as his microscope will we be able to grasp the full complexity of the natural world.¹ His detailed engravings show us things that exist all around us, if only we could see them. In this paper I look behind Hooke's images and explain the practices and materials with which Hooke constructed his observations. Primarily, this is intended as a contribution to a growing amount of historical literature that focuses on the practical skills and aims of early modern thinkers and accepts that, in reaching out to grasp the world, they evaluated their instruments and methods in ways unfamiliar to us now.² When Samuel Pepys called Hooke's microscopy 'ingenious', what did he mean?³ This is especially important to remember when thinking about things such as the microscope, which retains a connotation of bringing us closer to the truth about things. People and things are constantly being 'put under the microscope' to reveal details that we missed on

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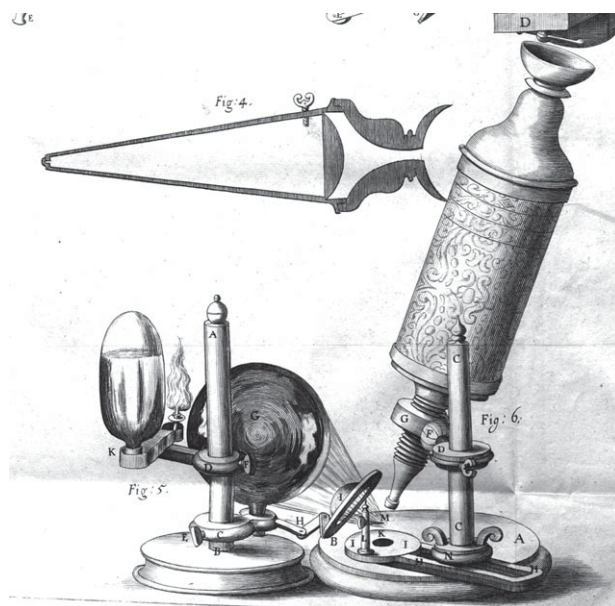


Figure 1. Hooke's microscope, detail from *Micrographia* scheme 1, opposite p. 1. The objects that Hooke has labelled 'Fig:4' and 'Fig:5' are instruments described below.

first glance—details that are assumed to make our impressions of that person or thing more true. But although the seventeenth-century microscope was an instrument of knowledge in that it was implicated in resolving the pressing epistemic issue of the time—the difference between the objects of the world and our sensory impressions of them—the relationship between the microscope's materiality and what it showed has been little discussed. I begin with mundane details about the former, and move towards epistemic claims about the latter.

Hooke first practised microscopy with Christopher Wren, Thomas Willis and others in the experimental circles of Oxford in the 1650s and early 1660s, but he began his observations for *Micrographia* in earnest after moving to London in 1663.⁴ Before getting accommodation in Gresham College in the following year, where he would live for the rest of his life, he lodged with Katherine Jones, Lady Ranelagh, at her house in Pall Mall.⁵ This was a decade before Robert Boyle, Lady Ranelagh's brother, asked Hooke to design a laboratory for the house, and at this earlier time Hooke had for his work a simple room in which a large, south-facing window admitted essential sunlight.⁶ On a desk near the window he placed his instrument. 'The *Microscope*, which for the most part I made use of,' Hooke wrote in *Micrographia*, 'was shap'd much like that in [figure 1].'⁷

It was about 'six or seven inches long, though, by reason it had four Drawers, it could very much be lengthened, as occasion required.' There were 'three Glasses; a small Object Glass ... a thinner Eye Glass ... and a very deep one' in the middle of the tube. This last—a field lens, to increase the field of view—could be added or removed, again as occasion required.⁸ This microscope was made by Richard Reeve, and was probably bought for Hooke by Boyle, who was still his patron at this time.⁹ Hooke was not yet being paid by the Royal Society, and a microscope was probably more than he could afford by himself: when Pepys bought one from Reeve in 1664 it cost him £5 10s.

He justified the ‘great price’ with the thought that it was ‘the best [Reeve] knows in England, and he makes the best in the world.’¹⁰

Given the microscope’s role in crossing the divide between our limited knowledge and the vast expanse of nature, Pepys’s casual superlative hides complexities that are not at all obvious. To see what the ‘best’ microscope was, it will be helpful first to say something about how the microscope was understood by Hooke, Pepys and their community. Despite the relative novelty of the instrument, the word ‘microscope’ had quite a particular meaning in the mid seventeenth century. As Christoph Lüthy and Catherine Wilson have both pointed out, magnifying lenses had been in use in places such as scriptoriums and artisans’ workshops for centuries before *Micrographia*, and Renaissance naturalists often used single-lens magnifiers, commonly known as ‘flea glasses’, for their work.¹¹ Before the middle of the seventeenth century, though, people rarely advertised their work as the product of an instrument, as Hooke did.¹² In the 1620s and 1630s there was a swell of interest in magnification, which birthed the ‘microscope’ as a philosophical instrument. Johann Faber coined the name in response to Cornelius Drebbel’s design of two lenses separated by a short tube, but the word denotes any instrument for examining small things, and many early ‘microscopes’ were single-lens instruments, much like flea glasses. The invention of the microscope was not the design of a new instrument but a redescription of an old tool. Or, as Lüthy has put it: ‘the microscope was never invented.’¹³ Most of the novelty lay in philosophers’ hopes that lenses might reveal some important truth. As mechanical explanations of phenomena gained popularity over qualitative, Aristotelian ones, more and more philosophers sought glimpses of corpuscles—visions of the world as it really was, independent of our faulty perceptions. From Constantijn Huygens to Robert Boyle to Isaac Newton, many seventeenth-century philosophers expressed their hopes that good enough microscopes would reveal such fundamental constituents of nature.¹⁴ They often idealized the instrument’s form and function together, and as its purpose became to produce knowledge of the smallest parts of nature, improving the instrument usually meant improving its lenses to meet the predictions of theoretical optics. As Henry Power suggested, ‘if the Dioptricks further prevail, and that darling Art could but perform what the Theorists in Conical sections demonstrate, we might hope, ere long, to see the Magnetical Effluviiums of the Lodestone, the Solary Atoms of light[,] . . . the springy particles of Air.’¹⁵

For Hooke, the microscope was a different instrument. He agreed ‘that which has been already done (to assist the sight) ought not to content us, but rather to incourage us to proceed further.’ However, he suggested, we ought to both ‘attempt greater things in the same, and different wayes.’¹⁶ Optical magnification was not the only way to assist the eye:

’Tis not unlikely, but that there may be yet invented several other helps for the eye, at much exceeding those already found, as those do the bare eye, such as by which we may perhaps be able to discover living *Creatures* in the Moon, or other Planets, the *figures* of the compounding Particles of matter, and the particular *Schematisms* and *Textures* of Bodies.¹⁷

If we were to see the fundamental particles, it would not be through microscopes but ‘other helps’ yet to be invented. My point is not to separate Hooke from his experimental community—they all admired the microscope and hoped for important truths from it. The aim of his microscopy was still the visual confirmation of the small constituent parts of nature crucial for mechanical explanations, even if he sought instead the geometric elegance of figures in frozen urine, the minute spiders that hide in sage leaves and cause

their bitterness, or the air-filled pores that buoy up wood so that it floats on water. It has been well established that as much as mechanical philosophers might have hoped for evidence of corpuscles or explanations of phenomena in terms of them, such hopes were often hyperbolic. Experimenters sought ‘intermediate explanations’ that, though not absolutely reductive, still explained things without reference to our experience of them.¹⁸

The point of looking at Hooke is to consider the use of a microscope by someone who regarded it so highly as a means of expanding natural knowledge. It was not only an emblem of a new style of inquiry to which people attached optimism for future insights; it was also used to show people things they had not seen before. What is important to notice about Hooke’s microscopy is that he did not idealize a particular form of the instrument, and he was willing to adapt almost any part of his tool. ‘I have made several other Tryals with other kinds of *Microscopes*, which both for *matter* and *form* were very different from common spherical Glasses’, he admitted in *Micrographia*.¹⁹ He selected certain specimens, prepared them with mechanical and chemical processes, and mounted them for display in numerous ways. He lit them from all angles, with varying intensities, from various sources, and used lenses of different sizes, shapes and materials. For Hooke, microscopy encompassed practices that manipulated a loosely connected system of materials extending from the ants he kept in a jar on his desk to the sunlight admitted by his window.

This paper focuses on three main aspects of microscopy: lenses, light and specimens. In the first, Hooke’s microscope explodes into a wide variety of forms and configurations, before coming back together into Reeve’s fashionable tooled-leather tube, for if Hooke’s conception of a microscope allowed ‘great variety’, his physical instrument did not always follow suit. ‘I find generally none more useful then that which is made with two *Glasses*, such as I have already describ’d.’²⁰ Secondly and thirdly, I show why and how his preference necessitated ingenuity and skill in handling light and specimens, respectively, to the extent that these, much more than lenses, were the crucial parts of his instrument. We ought not think that the aim of a microscope is to refract rays of light, and that early microscopes did so badly. The aim is to provide a magnified image of something too small to be seen properly by the naked eye. The things that enabled microscopy—light, refraction through different media, the indefinite complexity of nature—were the same things that made it difficult. Historicized appropriately, what could have seemed like practical solutions to technical difficulties resolve into techniques and parts of Hooke’s microscope.

Albert van Helden made a similar point about early telescopes. In the seventeenth century, telescopes increased in length, which permitted greater fields of view and resolving power. These improvements had little to do with the prescriptions of theoretical optics, and everything to do with practical experience and skill.²¹ Van Helden’s twofold aim was ‘to discuss the role played by the science in the development of the telescope, and second, to attempt to assess the influence of the telescope on scientific ideas in the seventeenth century.’²² The broadest point of my paper is a somewhat less elegant microscopical parallel: a better understanding of the relationship between the downward-looking instrument and empiricist, experimental philosophy. How much was the microscope understood in terms of theoretical optics, and how did it influence early modern ideas of seeing, particularly of seeing the truth? In 1713 George Berkeley, perhaps the most consistent empiricist of the British tradition, wrote that ‘microscopes make sight more penetrating, and represent objects as they would appear to the eye in case it were naturally endowed with a most exquisite sharpness.’²³ A close look at Hooke’s microscopy, though, shows that it was a move away from ‘natural’ vision and towards manipulative skills.

Material practices, often counter-theoretical or based on conflicting ideas, were the things that would bring human understanding closer to the true nature of things.

Finally, I conclude by relating these practices to the famous results of Hooke's work—the images of *Micrographia*. Lüthy has noted the need to understand 'epistemic images' such as these within their specific historical context.²⁴ Hooke's stable and enduring images take on new practical and epistemic significance when placed against the background of the constant flux of his microscopy.

LENSES: THEORETICAL NON-PROBLEMS AND THEIR PRACTICAL SOLUTIONS

Hooke knew that his microscope magnified objects because it refracted the light bouncing off them, stretching the images that entered his eye. In his compound microscope, this happened twice, by 'first, augmenting the figure in the Tube, by the smallness of the object-Glass, and the length of the Tube: and secondly, by the augmenting that image in the bottom of the eye; and that is by the Eye-glass.'²⁵

He also knew that refraction had effects other than magnification, two of which have fiddly positions in the history of optical instruments. First, rays of sunlight disperse into colourful spectra when refracted through a lens. Looking through an instrument such as a microscope or telescope, an observer views an image that is tinged by a halo of colour. Second, only the centre of such an image would be in focus, even given a light source of one single colour. A spherical lens made of uniform material has a focal line rather than a focal point—it refracts rays incident on its circumference to a different point from those rays incident on its centre. These days we call such undesirables 'aberrations', respectively 'chromatic' and 'spherical' aberrations. However, this term first appears in the mid eighteenth century, and even though the effects were studied and discussed in Hooke's time, the terminology is anachronistic when applied to him. 'Aberration' has a moral tone of deviation from a natural state, and indeed refers to optical phenomena that diverge from the straight-line predictions of paraxial optics. Hooke recognizes them as 'inconveniences [which] are such, as seem inseparable from Spherical Glasses.'²⁶ His more pragmatic term apparently acknowledges colours and smudges as mere aspects of the image that one sees through a lens, rather than divergences from an expected result. Hooke's ideas about light and refraction influenced his thoughts about magnification, but he did not privilege optics above other concerns.

In their debate over theoretical optical ideas in the early 1670s, Hooke and Newton discussed whether refraction could ever produce an achromatic image.²⁷ Newton's novel insight into spectral colours was that such colours were fundamental, and white light was a mixture. Different colours of light (whatever might separate them metaphysically) would always refract at different angles. Newton concluded that truly achromatic lenses could never be made from a uniform material, but only possibly by placing two materials with different refractive qualities adjacent to one another so they 'perform[ed] the office of *one Glass*'.²⁸ Indeed, when achromatic lenses were reliably made, by the middle of the eighteenth century, they were constructed from two types of glass in contact.²⁹ Hooke, in contrast, thought that colours resulted from modifying white light.³⁰ The difficulty of magnifying by refraction without producing colours was 'very great', he admitted, 'but yet not insuperable'.³¹ He experimented with reflection microscopes, but also persevered with refraction instruments, to which I return below.

Nor did theory suggest definitive improvements to the microscope for the case of what we now call spherical aberration. Descartes had shown in his *Dioptrique* (1637) that lenses that were hyperbolic rather than spherical would refract rays to a sharp point, and so would not suffer the problematic fuzziness.³² Unfortunately they did not exist. Theoreticians were not completely divorced from practitioners—the fairly determined effort to build machines that would grind hyperbolic lenses, largely prompted by Descartes's book, was an arena in which, as Fokko Jan Dijksterhuis has shown, 'contemplation and manipulation [were] almost completely interwoven.'³³ Mathematicians, lens makers, and instrument makers—including Richard Reeve in the early 1640s—sought to improve magnification devices.³⁴ They were not without successes: in 1668 Francis Smethwick produced before the Royal Society a telescope made with aspherical lenses that he had ground, and which outperformed the 'common (read: spherical), yet very good' instrument against which the Society tested it.³⁵ However, microscopists were not always interested in the hyperbolic lenses that instrument makers tried to grind for them. As Van Helden wrote of the early years of telescopy, such significant advances were made in spherical lens grinding that hyperbolic dreams were rendered practically superfluous.³⁶ In *Micrographia*, Hooke skimmed over non-spherical lenses as a remote future hope. What concerned him more was that most spherical lenses were useless. 'There may be perhaps ten wrought before one be made tolerably good', he complained, and went on to detail his design for a machine for grinding spherical lenses, emphasizing its ease, exactness and speed.³⁷

One practical problem even with good spherical lenses was that their viewing area must be restricted to a small patch in the centre of the lens. 'As for *Telescopes*,' Hooke concluded on the basis of this consideration, 'the only improvement they seem capable of is the increasing of their length.'³⁸ A longer telescope could house a larger object lens and therefore a larger aperture, and the size of this theoretically determines the instrument's resolving power. However, as Van Helden noted, in the latter half of the seventeenth century Guiseppe Campani was able to produce lenses of much more refined resolution than Galileo's earlier instrument, despite their both having a similar aperture.³⁹ The difference was purely in the glass grinding.

Hooke may have understated the case for telescopes, but in any case he thought that improving microscopes was a more creative affair. He had many tricks up his sleeve, some involving lenses themselves, and some not. He mentions that not only had he used a microscope with spherical lenses, but also

I have made a *Microscope* with one piece of Glass, both whose surfaces were *plains*. I have made another only with a *plano concave*, without any kind of reflection, divers also by means of *reflection*. I have made others of *Waters, Gums, Resins, Salts, Arsenick, Oyls*, and with divers other *mixtures* of *watery* and *oily Liquors*.⁴⁰

Although he does not say what prompted this experimentation, presumably it was because of the different refractive qualities of different media, or because he was trying to mould them into different shapes.⁴¹ Any implication of a determined fascination with lenses, though, is quickly belied by Hooke's general rule of thumb regarding them. Lenses provided magnification and were the focus of most people's attention on the microscope, but Hooke's general impression was 'the more the worse'.⁴²

He actively sought to *reduce* the number of refractions in his microscopes, because—owing to restricted apertures—'always the fewer the Refractions are, the more bright and clear the Object appears.'⁴³ He rarely made use of the third lens he could insert in his

Reeve microscope, and he moved away from Drebbel's instrument from whence the name 'microscope' came. He made for himself single-lens instruments, simple microscopes of the style more commonly associated with Dutch microscopy, especially Antoni van Leeuwenhoek. In July 1663 he reported to Boyle: '[I] made a microscope object glass so small, that I was fain to use a magnifying glass to look upon it.' This first attempt 'did not succeed so well as I hoped; but I suppose it might be, because this being the first I had made, the tool was not very true, nor my hand well habituated to such an employment.'⁴⁴ He practised, and after breaking the first one he packaged, sent one off to Boyle in November 1664, claiming it would 'magnify the object, and make it as clear, when conveniently placed, as one of Mr. Reeve's largest.'⁴⁵ In the preface to *Micrographia*, Hooke described the process of making these tiny lenses by holding a shard of glass over a flame until it melted and a droplet formed. He filed the droplet into a bead and polished it smooth, then stuck it with wax into a small hole punched through a metal plate. Pinning an object very close to one side of the bead, and with his eye very close to the other, Hooke found it would 'both magnifie and make some Objects more distinct then any of the great *Microscopes*.'⁴⁶

Ofer Gal has called Hooke's willingness to replace two lenses with one 'anti-theoretical'.⁴⁷ The theory behind practical optics in Hooke's time was, largely following Kepler, based on the interactions of two lenses of different shapes or sizes. Hooke's instrumental ingenuity followed a different rationale: to achieve a clear image. The best instrument for Hooke was that which enabled him to fulfil his immediate task of drawing pictures of small things, and for this he strove to reduce the number of refractions to get a brighter image. A single-lens microscope was not the extent of his 'anti-theoretical' ingenuity. When examining a liquid with a simple microscope it was possible to simply smear the liquid on the lens itself: 'this liquor being of a specifique refraction, not much differing from glass, the second refraction is quite taken off, and little or none left but for that of the convex side of the Globule next to the eye.'⁴⁸

The result was an instrument 'capable of the greatest clearness and brightness that any one kind of Microscopes can possibly be imagined susceptible of.'⁴⁹ A small glass bead smeared with liquid was in a sense the perfect form of the instrument. Despite this, he hardly used it. Later, Hooke would lament that none of his colleagues seemed to have adopted simple microscopes, or even remember him telling them about it, but even by the time *Micrographia* was published Hooke himself was making little use of them.⁵⁰ He recognized that 'tis possible with a single Microscope to make discoveries much better than with a double one', and he could make them at home with some old glass and a lamp—surely an advantage to a waged Curator new to London and lodging in someone else's townhouse.⁵¹ But Hooke repeatedly complained that he found them 'very troublesome to be us'd', and they were 'offensive to my eye'.⁵² He left them to 'those whose eyes can well endure it', and sought a different way to reduce the number of refractions in his instrument.⁵³ He filled his compound microscope tube with water. This is the object in cross-section labelled 'Fig:4' in figure 1.

With the tube filled with water, light was refracted less both leaving the object lens and entering the eyepiece lens. The instrument recalls Newton's suggestion that a single lens could be constructed from several different materials, and even more closely resembles Descartes's idea that looking through a tube full of water functionally changes the shape of the eye.⁵⁴ Unfortunately, optical performance was again trumped by practical matters. Unspecified 'inconveniences' meant that Hooke hardly used this instrument.⁵⁵ The water

would have to be incredibly clear, and the tube very stable, well made and water-tight. Perhaps it leaked, or the water softened the wax seal around the lenses and caused them to shift.

For Hooke, practical solutions to the inconveniences of magnification made the insights of theoretical optics marginal. But convenience outweighed both theory and his working rules of thumb, and for all his experimenting, Hooke returned to his store-bought microscope tube. Doing so meant he had to manipulate things other than lenses.

LIGHT: THE INVISIBLE MATERIAL

Restricting the useable lens area to its centre alone meant a more uniform focus, less aberration and greater resolution. The side effect was that less light could enter, and the image would be darker and less distinct. Telescopes grew larger and larger to maximize lens area, but microscopists had to find a different solution. '[G]ive therefore light enough to the object', Hooke realized, 'and you may increase the image at the bottom of the eye to what proportion you shall desire.'⁵⁶ Manipulating light was the key to successful observations.

The Sun was an unreliable resource. The light through Hooke's window was often not bright enough to make observations by, and even on sunny days he found he rarely completed one in daylight hours.⁵⁷ Two devices outside the microscope tube quickly became vital parts of his microscope. One was a glass globe full of water—a 'scotoscope'. This is the orb marked G in figure 1. 'By means of this instrument ... the small flame of a Lamp may be cast as great and convenient a light on the Object as it will well indure.'⁵⁸ It seems to have been a fairly standard means of light amplification in the seventeenth century. When Pepys bought his microscope from Reeve, it likewise came with this 'curious curiosity [to see] objects in a darke room with'.⁵⁹ Often Hooke would diffuse the amplified light through a piece of oily paper so the specimen could be evenly lit, without hard shadows or glare.⁶⁰ The other was the lamp itself. Hooke worked hard at improving lamps, and later published designs for several that would burn with an even flame and for as long a time as possible—both strong desiderata for the microscopist.⁶¹ As well as providing enough light for a bright, magnified image, and being able to make observations at his nocturnal convenience, lamplit observations had two further advantages. First (although he does not mention this), observations made using flame from an oil lamp presumably suffered less from chromatic aberration than those made in white sunlight. Second, Hooke could easily change the angle of the light. This latter technique was the centrepiece of Hooke's microscopical method.

In fact, as well as using a lamp to change the position of his light source, Hooke could also swivel his microscope tube. His drawing in figure 1 seems to be the first depiction of a microscope mounted by a ball and socket onto a pillar, rather than sitting immobile on a tripod. The way he describes the instrument in his later Cutlerian lecture, 'Microscopium', implies that this was his own innovation—he detached the tube Reeve made from the 'common pedestal' and 'instead thereof I fix[ed] into the bottom ... a cylindrical rod of Brass or Iron.'⁶² The arrangement was highly mobile: he could twist his lenses and specimens into 'all kind of positions, both to my Eye and the Light.'⁶³

The detail with which he explains this in both *Micrographia* and 'Microscopium' indicates the importance he placed on this mechanical mobility, and it was something he criticized others for not paying enough attention to. When he reviewed Filippo Bonanni's

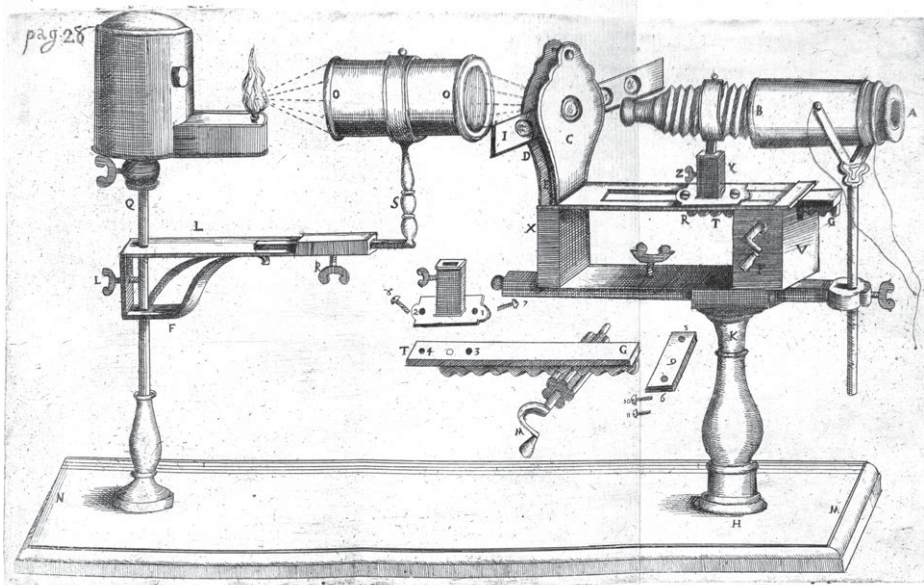


Figure 2. Filippo Bonanni's horizontal microscope, from his *Observaciones circa Viventia, Quae in Rebus Non Viventibus Reperiuntur* (Rome, 1691), p. 28. (Image courtesy of Université de Strasbourg, Service Commun de la Documentation (France).)

microscopical work in 1693, Hooke scarcely mentioned the optical quality of Bonanni's lenses, but criticized him for using a microscope with 'too much apparatus and clutter and yet ... wanting of many accommodations for examining or as it were handling & turning the Object into all postures & for all lights' (see figure 2).⁶⁴

Hooke's earlier criticism of Henry Power is similar, if more oblique. He does not describe Power's instrument (which was also made by Reeve), but instead the variety of other ways a fly's eyes can appear in addition to the single appearance that Power saw. In fact, Hooke repeatedly emphasized that objects look like one thing from one angle or in one light, and another in another.⁶⁵ Absences looked like presences; shadows looked like dark patches on the object. He agreed with Power that under certain light flies' eyes looked like a lattice of tiny holes, but added that in full sunlight they turned into a surface of bright nails or pyramids.⁶⁶ As Meghan C. Doherty and Matthew C. Hunter have both emphasized, rather than find a single best way to illuminate something, Hooke found it necessary to vary the angle and quality of light, and be wary of those features of the image that altered.⁶⁷ As I return to below, Hooke's impression of an object came not through glimpsing one clear view of it; many different appearances should be collated.

Both the pillar and the tripod mounts persisted into the eighteenth century, despite Hooke's consistently emphasizing the benefits of the former, both in *Micrographia* and later lectures.⁶⁸ That not everyone adopted his design perhaps indicates the different abilities and priorities of contemporary microscopists; however, for Hooke's part, successful microscopy had more to do with bouncing the right amount and quality of light off his specimens and through his lenses than with the lenses themselves.

SPECIMENS: SEEING WHAT WAS THERE

The final important part of the instrumental setup was of course the subjects themselves. Preparing a specimen suitably was perhaps the hardest thing of all for a microscopist. Marian Fournier has noted that although this aspect of microscopy was equally if not more important in determining research programmes with the instrument, it was much less discussed by early microscopists than were optical issues.⁶⁹ Some of the difficulties and implications of specimen preparation can be recovered from scattered comments and one episode of Hooke's work in particular. In her philosophical story *The Description of a New World, Called the Blazing World* (1666), Margaret Cavendish questioned the usefulness of microscopy with an absurd request: to see a whale under a microscope. The hapless experimenters readied their largest instrument, 'but alas! The shape of the whale was so big, that its Circumference went beyond the magnifying quality of the Glass.'⁷⁰ Cavendish was exaggerating a real constraint of microscopes, not simply that they could not cope with giant objects—they would not be called 'microscopes' if they could. But even within the microworld, the form of any particular microscope severely restricts what it can be used for. Hooke noted that because things need to be placed so close to the lens of a simple microscope, those instruments are all but useless for viewing opaque objects. Attach a fly to the underside of the glass bead and it cannot be illuminated from above or the side, but only behind, casting a giant shadow on the microscope lens.⁷¹ On the other hand, when using a compound instrument, Hooke found 'the transparency of most Objects renders them yet much more difficult then if they were *opacous*'.⁷² Loyalty to a particular subject matter could determine the form of the instrument used, and vice versa.

Hooke's microscopical inspiration was a series of insect drawings that Wren had given to Charles II, and he was probably further prompted by Power's observations, also made with a Reeve compound instrument. Despite his ability to improvise other instruments, to some extent Hooke's chosen subjects helped determine the instrument that he used. Because he was increasingly frustrated by simple microscopes, the reverse also became true. While he—and Power—used mainly compound microscopes to look at (mainly) insects, plants and seeds, simple microscopists such as Leeuwenhoek and Jan Swammerdam wrote much more frequently on anatomy, blood cells, spermatozoa, and the tiny nematodes in liquids. When Leeuwenhoek wrote to the Royal Society and described the tiny animals he saw in water infused with pepper, the two programmes crossed paths. In October 1677 Hooke dusted off his old instruments. 'I put in order such remainders as I had of my former Microscopes (having by reason of a weakness in my sight omitted to use them for many years) and steeped some black pepper in River water.'⁷³ Little thereafter was straightforward. The episode demonstrates how tricky it could be simply to see what there was to see, even if you knew it was there.

Ian Hacking has said that for the microscope to become a successful and fashionable parlour toy, it needed to be packaged with a box of specimen slides to look at, which would routinely cost more than the instrument itself.⁷⁴ This limited the objects one could view and therefore the microscope's usefulness as a tool of discovery, but without such preparations most people could not see anything at all. After Pepys bought his microscope, he and his wife sat down to read Power's *Experimental Philosophy* to 'enable me a little how to use [it] and what to expect', but still had 'great difficulty before we could come to find the manner of seeing any thing.'⁷⁵ When Hooke sent Boyle his first simple microscope, he thoughtfully attached a 'small brush of hairs' for him to

look at.⁷⁶ In Hacking's words, 'You did not just put a drop of pond water on a slip of glass and look at it.'⁷⁷ For one thing, as Hooke tells us, the slip of glass needs to be 'very clear and thin[,] . . . very smooth and plain on both sides, and clean from foulness', so that artefacts in the glass would not be mistaken for discoveries.⁷⁸ For another, the pond water must have in it the things you wish to see. On 1 November Hooke looked for Leeuwenhoek's pepper-worms for the first time and saw nothing.⁷⁹

It was not clear to the Fellows of the Royal Society what caused the failure. Leeuwenhoek bragged about the tiny size of the animals he could see, and he refused to divulge secrets of his microscope design.⁸⁰ Perhaps Hooke's microscope was not strong enough. Then again, he had made this first observation with plain water, not infused with pepper.⁸¹ Perhaps there were just no animals to see. The Fellows resolved to change both the instrument and the specimen for the next meeting, while Hooke himself emphasized the importance of the interface between the two—the specimen mount. Leeuwenhoek used thin glass pipes to hold his liquid, and Hooke conjectured that the pipes themselves might act as magnifying glasses, doubling the effect of viewing them through a lens.⁸² Hooke preferred his mounts to be 'hardly perceivable by the eye'; he spread liquids on a thin plate of mica, or used two plates to squash flat uneven substances such as fats or oils.⁸³ Small threads such as tendons he would stretch out between two tweezers.⁸⁴ Leeuwenhoek's method, wrote Hooke, was very 'ingenious, and very convenient' for simple microscopes, but less so for compound ones.⁸⁵

Even so, at the next trial on 8 November, Hooke had a more powerful compound microscope, which he had adapted to hold Leeuwenhoek-type glass tubes. A tube was attached to a perforated brass plate, which could slide along another piece of brass fixed below the object lens, allowing different angles and views.⁸⁶ The tube was filled with water steeped with pepper for three days. But still there were no worms. Again the Fellows conjectured why not. Thomas Henshaw blamed the season. It was late autumn; perhaps this was not the time of year for pepper-worm generation. Daniel Whistler thought that maybe the black flecks of pepper they could see floating about were Leeuwenhoek's 'imagined creatures'.⁸⁷ They decided against this quite reasonable response for two reasons, one evidential and one testimonial. Leeuwenhoek had written about seeing the worms both alive and dead. The floating specks were clearly not swimming creatures, raising the question of how he could have noticed a difference if they were all he had seen. Perhaps more importantly, the Dutchman's first observation had been also witnessed by two ministers, a public notary and five other 'persons of good credit'.⁸⁸ Such 'virtual witnessing' helped to universalize what was otherwise a private and contestable experience, and was an important part of how Royal Society Fellows themselves vindicated their experimental endeavour.⁸⁹

After the second failure, Hooke fell back on explaining how, by keeping both eyes open, he could measure the magnification of a microscope. It was suggested to him that next time he should put this skill to use and bring a more powerful microscope. The majority view was to equate the success of an observation with the size of the image.⁹⁰ In fact, though, Henshaw had not been far wrong: what was needed was patience. Microscope design was not the only detail that Leeuwenhoek had not divulged: there was also the fact that the worms needed time to generate inside the pepper water. Hooke began to notice them the following week: 'as if I had been looking upon a Sea, I saw infinite of small living Creatures swimming and playing up and down in it, a thing indeed very wonderful to behold.'⁹¹ At the meeting on 15 November he showed them to an excited crowd.

Charmed onlookers saw tiny egg-shaped bubbles wriggling to and fro with an erratic movement that convinced them they were seeing animals: 'there was no longer any doubt of Mr. Leewenhoeck's discovery.'⁹²

People suggested iterations of the experiment—replace the pepper with wheat, barley or nothing; replace the water with blood or another liquid—and speculative explanations.⁹³ Hooke thought that the worms might have hatched from eggs laid on the pepper before it was steeped, but Henshaw, Wren and William Holder argued that it generated them directly. Henshaw gave an analogous case as support: the pepper's heat fermented the mixture and produced worms, as also happens when horses' tails or lute strings are steeped in water and generate snakes.⁹⁴ It was a triumph of collaborative experimental philosophy. An experiment perfected in private by Hooke was repeated in front of witnesses, and a lively discussion followed.

A week later Hooke reported that wheat, barley, oats, aniseed, peas, beans, '&c.', all indeed generated animals too when left in water, although these animals had different shapes and moved differently. He also brought back the pepper-worms, which had grown, and through a microscope that was 'very much improved since the last Day', some Fellows thought they could see 'Leggs or finns, but others could not Discerne them.'⁹⁵ This brings me to my final and most epistemological point about the craft of microscopy. Even the first successful pepper-worm observation was not as straightforward as the minutes describe, as Hooke later admitted in 'Microscopium':

when the water began to dry off, the bending of the superficies of the liquor over their backs, and over the tops of other small motes which were in the water made a confused appearance, which some not used to these kind of examinations, took to be quite differing things from what they were really; and the appearances here are so very strange, that to one not well accustomed to the phaenomena of fluids of differing figures and refractions, the examinations of substances this way will be very apt to misinform, rather than instruct him.⁹⁶

The observation was a temporary construction reliant on a fragile system of material contingencies. Even a difference of a few minutes could change a subject's appearance, as a liquid evaporated or a cloud obscured the Sun.⁹⁷ It was because of this that Hooke emphasized that he never began drawing a subject before he had made 'many examinations in several lights, and in several positions to those lights.'⁹⁸ Doherty has argued that Hooke's ability to discover the 'true form' of an object among these shifting impressions stemmed from his familiarity with the vocabulary of visual artists.⁹⁹ He noted variations and could interpret a white stripe as a reflection, or a patch of colour as an artefact of his lenses. Samuel Y. Edgerton Jr made a similar point about Galileo: the latter's education in Florentine *disegno* enabled him not only to draw evocative images of the Moon but even to see its patches of dark and light as shadows and mountains.¹⁰⁰ My aim in this paper so far has been to extend our knowledge of Hooke's methods to the creation of these shifting appearances in the first place. The microworld was not merely there for the looking, even through a good enough instrument. If there is an analogy between Hooke's method and Galileo here too, it is with the 44 days over which the latter observed and mapped the Medicean Stars in order to notice that they were not fixed against the background but orbited Jupiter as moons. Such observation is a process, not a discrete experience. What the pepper-worms story suggests is that the visions that Hooke's microscope provided necessitated such a process for him too. What he could see

resulted from a complex interaction between his lenses, the light travelling through them, and the natural world. A change in any could change his view.

PICTURES: THE END RESULTS

When Galileo published his observations of the Medicean Stars, he did so with several schematic images that represented only their motion accurately—this was the aspect of them that interested him and allowed him to show that they were real moons, not optical artefacts or background stars.¹⁰¹ With a few exceptions, Hooke's published images collapsed his 'many examinations' into one naturalistic and lifelike image of a subject, and he sometimes deliberately occluded the fact that they were mosaics constructed from many views. This naturalism was what he was interested in communicating with his readers, not his experiences themselves.

He begins a picturesque account of an observation in *Micrographia* with 'Reading one day in *Septemb.*'¹⁰² We can imagine him, blue eyes skimming the lines of a traveller's tale as an autumn morning breezes through the window of his room in Lady Ranelagh's house.¹⁰³ About to turn the page, he is distracted: 'I chanced to observe a very smal creature creep over the Book I was reading, very slowly; having a *Microscope* by me, I observ'd it to be a creature of very unusual form.'¹⁰⁴ Here we read of the microscope as an easily used instrument that can reveal the hidden details of the things surrounding us. His illustration of this 'Crab-like Insect' is the creature with eight pointy legs and two large claws growing out of its head (figure 3).

However, any suggestion that his drawing is how the creature appeared to him through a magnifying lens is belied by the messiness and uncertainty of the painstaking craft of microscopical observation. As we have seen, a lot needed to happen to illustrate in such detail a tiny insect spied scuttling over an uneven black and white background. In this case, we can see some more steps that Hooke took to construct the true form of the Crab-like Insect by looking at a draft inserted in a notebook belonging to John Covell, which Janice Neri has identified as Hooke's early work (figure 4).¹⁰⁵

The drawing is dated 11 April 1661. Despite the different date, and the fact that he also says he only ever found one specimen, it is surely a draft of the published image. Not only are their shapes similar, the creatures are also depicted in the same pose, one claw up, one down, and they are reversed left to right, presumably as a result of being engraved and printed.¹⁰⁶ Other more substantial changes reveal the relationship between the material practice I have described above and the finished images.

In *Micrographia* the creature appears with a liveliness and naturalism that characterizes all the flora and fauna inhabiting the book. Its legs splay out in movement, and its claws seem to clack open and closed as it almost chases a mite across the page. 'A Kind of Teek found creeping upon paper', Hooke disclosed about his draft, 'it was drawn dead.'¹⁰⁷ Although that gave him time to examine it, it also made such creatures shrivel unbeautifully, so they were no longer good models for lifelike drawings. Hooke learnt this early on in his microscopy, and continued to struggle with insect wrangling. In 1661 he described finding a beetle 'soe unruly I could not put his legges and body into a posture to drawe him alive[,] wherefour I cut off his head.'¹⁰⁸ He later tried fixing an ant's feet with glue, but it would still 'so twist and wind its body, that I could not any wayes get a good view.'¹⁰⁹ Consequently, he devised his famous method of dunking an ant in brandy

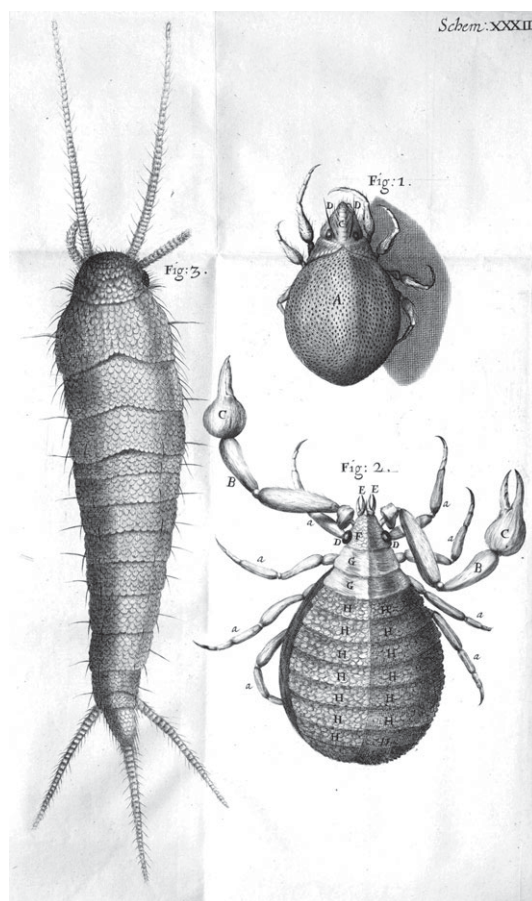


Figure 3. *Micrographia*, scheme 33, opposite p. 207.

to make it sit still—he found that an ant left in fortified wine for an hour was immobilized for the same length of time. For the ant's portrait in *Micrographia*, Hooke did this several times over, catching it and dunking it again when it stirred and ran off. Each time, he picked up the paralysed insect and used a pin to move its tiny limbs into 'what posture [I] desired to draw it.' What he relates took up at least a whole day, with the English sunlight in 'continual variation' through his window, morphing his subject's image through his lenses.¹¹⁰ Such frustrations of specimen preparation were common among early modern microscopists. Antoni van Leeuwenhoek reported spending several days killing more than 100 mosquitos while trying to get one good look inside the mouth of one.¹¹¹

Hooke and Leeuwenhoek make an interesting comparison on this point. When the scholar and travel writer Zacharias von Uffenbach visited Leeuwenhoek in 1710 he recorded seeing hundreds of microscopes, each with a different object attached.¹¹² Leeuwenhoek's workroom was also a showroom, with each small instrument dedicated to a single view of one tiny object, like so many little windows into the microworld. Similarly, when the Dutchman dedicated 26 of his microscopes to the Royal Society on his death, they arrived with

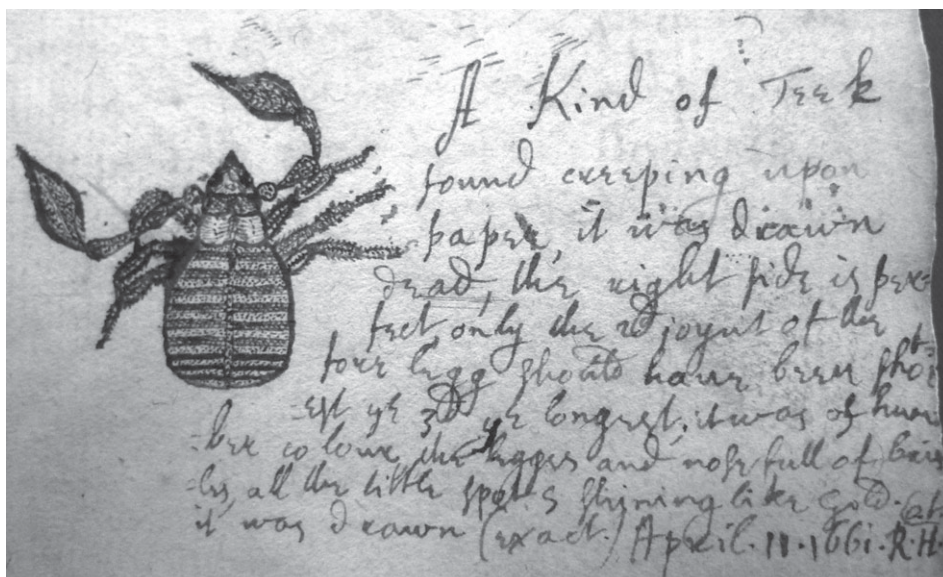


Figure 4. Draft of 'A Kind of Teek'. Detail from John Covel, 'Natural history and commonplace notebook', ca. 1660. (Copyright © The British Library Board, Add. 57495, f. 113v; reproduced with permission.)

specimens attached, or detached only by rough transit.¹¹³ Leeuwenhoek made a different microscope for each observation: they were discrete, self-contained units, each instrument a separate *experimentum*. He went to great pains to prepare each vision, and once prepared it stayed prepared. His method was similar to that which later allowed the popularization of the microscope: in the eighteenth century, practical introductions to the microscope by writers such as Henry Baker and George Adams focused largely on preserving and mounting specimens, providing amateurs with a collection of ready-made observations.¹¹⁴

In contrast, the objects that Hooke depicted in *Micrographia* quite often did not exist at all.¹¹⁵ Occasionally he managed to share an observation with others—as with the pepper-worms above, and as eyewitnesses' initials beside several drafts in the Covell notebook imply.¹¹⁶ But in general, if Lady Ranelagh had stopped by her lodger's room she would have seen ants resting in brandy or a beetle with no head. If she had put her eye to Hooke's lens, she might have glimpsed ambiguous parts of objects, shifting in colour or form as clouds crossed the Sun. She would not have seen the glorious, naturalistic detail of the images in *Micrographia*.

As Neri explains, figures 3 and 4 differ not only in terms of the amount of detail visible. Date and liveliness aside, the earlier picture shows an insect with six legs, whereas in *Micrographia* Hooke's 'true form' is of a crustacean with eight. Neri's explanation for this metamorphosis is that its claws made Hooke think of the creature as 'crab-like'. Unable to examine his (dead) subject again, but knowing that crustaceans have eight legs, he seems to have added this detail to his master drawing which then went to the engravers for publication.¹¹⁷ Hooke was willing to modify the information in *Micrographia* away from what he saw—or thought he saw—through the microscope.

Later, he would complain that natural historical drawings were too often left to ‘Mr. Engraver’s Fancy’, instead of being drawn by observers themselves.¹¹⁸ This is not hypocrisy, and my point is not to criticize him for disingenuity. Hooke’s micrographs are exemplars of epistemic images: illustrations that, as Lorraine Daston defines, ‘stand-in for the too plentiful and too various objects of nature, and ... can be shared by a dispersed community of naturalists who do not all have direct access to the same flora and fauna.’¹¹⁹ In this case, the ‘various objects of nature’ that he distilled for his audience could be the same insect’s eye viewed twice, on a cloudy and a sunny day, and his pictures communicated something that neither words nor accurate drawings of microscopical experience could. Figure 3 tells us that the Crab-like Insect exists; it does not matter if you cannot see it.

Again there is an illustrative comparison with Galileo’s work with early telescopes. Between his first drawings and the engravings published in *Sidereus nuncius*, a giant crater appeared on the face of the Moon. Mario Biagioli has claimed that Galileo’s images, inaccurate but realistic, succeeded in conveying ‘a philosophical point about the physical nature of the Moon not by representing it “the way it was” (that is, in its specificity), but by exaggerating the irregularities of the lunar surface, thus making them more generic.’¹²⁰ Through exaggeration, not mimesis, the Moon became more like the dented orb that Galileo wished to show it was. In *Micrographia*, Hooke likewise sought to illustrate a general point about the intricacy and orderliness in the nature that lives around us but beneath our attention. Crabs as real and complex as those living in the muddy banks of the Thames crawl unseen across your books on autumn mornings. ‘By the help of *Microscopes*, there is nothing so *small*, as to escape our inquiry’,¹²¹ Hooke asserts, and *Micrographia* demonstrates this not by depicting things as they looked through lenses, but by providing easily comprehended and naturalistic pictures.

Daston suggests that a change in the style of scientific illustration generally reflects the emergence of a new epistemic norm.¹²² Hooke was heralding a new style of natural inquiry: his images represent the utility of instruments and the importance of sharing personal knowledge. There is good reason to think his contemporaries understood that they did not show things readily available to anyone with a microscope. Pepys, for example, stayed up all night enjoying *Micrographia*, but was frustrated by his attempts with his own instrument. Also, although Hooke’s illustrations were no doubt influenced by Galileo, they owed more to Christopher Wren. While Hooke and Wren were together in Oxford in the 1650s, Wren worked on the illustrations for Thomas Willis’s *Cerebri Anatome* (1664).¹²³ As Martin Kemp and Nathan Flis have noted, Wren’s method did not involve projecting or tracing an image of the brain directly, but rather synthesizing and depicting knowledge he had learned from several dissections of different specimens injected with dye.¹²⁴ Neither Wren’s nor Hooke’s microscopical illustrations faithfully represent one particular view of an object; both combine the results of many observations, deductions and research. Interestingly, Thomas Sprat called Wren the ‘*Inventor of drawing Pictures by Microscopical Glasses*’, as though he agreed that technical skills like these were the crucial part of the exercise, rather than reproducing one’s experience, as earlier naturalists using flea glasses had done.¹²⁵

CONCLUDING REMARKS

Understanding early modern microscopy requires taking an inclusive view of what constitutes an instrument, and the realization that using it meant far more than merely

looking. Moulding lenses from arsenic, building lamps, arranging insect limbs on slides—all of these were aspects of Hooke's microscopy that he altered in his quest to show the intricacy of the mundane nature surrounding him. It was through these techniques, he showed readers of *Micrographia*, that natural knowledge would gradually be expanded.

We are now in a better position to see what the Royal Society's Fellows meant when they demanded a better microscope with which to see Leeuwenhoek's pepper-worms than we were at the beginning of this article, when Pepys claimed that Reeve makes the best microscopes in England. Hooke's aim was never to find the one perfect instrumental setup that would provide him with a single, clear view of any subject. The form of his microscope was not determined by theoretical optics but by his mechanical, optical and zoological ingenuity, as he balanced different considerations against one another to gradually uncover details about the minute objects he gathered around him. Once these had been uncovered, he drafted pictures that collated the various insights he had gained about his subjects, to share with his readers not a realistic impression of sight with a microscope, but his privileged knowledge of the microworld. Hooke's microscope was not an instrument of eye, as Berkeley later claimed, but of the hands.

NOTES

- 1 Robert Hooke, *Micrographia* (London, 1665); see especially the preface.
- 2 See especially Jim Bennett, 'Instruments and ingenuity', in *Robert Hooke: tercentennial studies* (ed. Michael Cooper and Michael Hunter), pp. 65–76 (Ashgate, Aldershot, 2006); and the (at the time of writing) ongoing research project at CRASSH in Cambridge, 'Ingenuity in early modern art & science' (<https://ingenuitocrassh.wordpress.com/>; accessed 6 October 2015).
- 3 Robert Latham and William Matthews (eds), *The diary of Samuel Pepys*, 21 January 1664/5 (G. Bell & Sons, London, 1972), vol. 6, p. 18.
- 4 John T. Harwood gives a table of the dates on which Hooke made his observations: 'Rhetoric and graphics in *Micrographia*', in *Robert Hooke: new studies* (ed. Michael Hunter and Simon Schaffer), pp. 119–148 (The Boydell Press, Woodbridge, 1989), at pp. 124–125.
- 5 Hooke never mentions any company at her house in this period, but Lady Ranelagh was an important member of a network of writers, activists and thinkers, and Charles Webster has speculated that in the 1640s the Invisible College may have met at her house: *The Great Instauration: science, medicine and reform 1626–1660* (Duckworth, London, 1975), p. 62. For more on Lady Ranelagh see Carol Pal, *Katherine Jones, Lady Ranelagh: many networks, one 'incomparable' instrument* (Cambridge University Press, 2012). The lodging arrangement was amicable, and although Hooke and Lady Ranelagh had their arguments, they were generally friendly. See, for example, Henry W. Robinson and Walter Adams (eds), *The diary of Robert Hooke* (Taylor & Francis, London, 1935), vol. 1, pp. 81 and 364. He visited often after moving out, sometimes to see Boyle, who moved there in 1668, and sometimes Lady Ranelagh. Margaret 'Espinasse counts at least 30 dinner visits in 1677 alone in her *Robert Hooke* (William Heinemann, London, 1956), p. 111.
- 6 Hooke, *op. cit.* (note 1), sig. D2v. For the laboratory see Robinson and Adams (eds), *op. cit.* (note 5), pp. 280ff. The earliest image of the building is from after it was rebuilt after the deaths of Boyle and Ranelagh: 'Pall Mall, South Side, Past Buildings: Nos 83–84 Pall Mall, Lady Ranelagh's House, Christie's, Board of Ordnance', in *Survey of London*, vols 29 and 30 (*St James Westminster*, pt 1) (ed. F. H. W. Sheppard), pp. 367–368 (London County Council, London, 1960) (<http://www.british-history.ac.uk/survey-london/vols29-30/pt1/pp367-368>; accessed 15 November 2015).

- 7 Hooke, *op. cit.* (note 1), sig. F1r. In keeping with much recent history of science, several authors and museums have recreated vision through early microscopes like these. See especially Brian Ford, 'The clarity of images from early single-lens microscopes captured on video', *Microsc. Anal.* **25** (2), 15–17 (2011), and the sources to which he refers, especially the Whipple Museum of the History of Science (<http://www.hps.cam.ac.uk/whipple/explore/flashpages/microscopes/>; accessed 14 October 2015) and the Channel 4 programme *Genius of Britain*, episode 1 (broadcast on 30 May 2010)). Ford's main point, with which this paper agrees, is that early modern lenses might well have been technically capable of producing very clear images, but only when used with great care and skill.
- 8 Hooke, *op. cit.* (note 1), sig. F1r.
- 9 This is A. D. C. Simpson's suggestion: 'Robert Hooke and practical optics', in Hunter and Schaffer (eds), *op. cit.* (note 4), pp. 33–61, at p. 43, fn. 36. For more on Reeve, see A. D. C. Simpson, 'Richard Reeve—the "English Campani"—and the origins of the London telescope-making tradition', *Vistas Astron.* **28**, 357–365 (1985).
- 10 Latham and Matthews, *op. cit.* (note 3), 13 August 1664, vol. 5, p. 240. This seems roughly the same price as a printing press, and one-fifth of the cost of an air pump: Adrian Johns, *The nature of the book: print and knowledge in the making* (University of Chicago Press, 1998), p. 76; Steven Shapin and Simon Schaffer, *Leviathan and the air pump: Hobbes, Boyle, and the experimental life* (Princeton University Press, 1985), p. 34.
- 11 Christoph Lüthy, 'Atomism, Lynceus, and the fate of seventeenth-century microscopy', *Early Sci. Med.* **1** (1), 1–27, (1996), at p. 4; Catherine Wilson, *The invisible world: early modern philosophy and the invention of the microscope* (Cambridge University Press, 1995), ch. 2.
- 12 Catherine Wilson, 'Aesthetic appreciation of nature in early modern science', in *Vision and its instruments: art, science, and technology in early modern Europe* (ed. Alina Payne), pp. 49–68 (Pennsylvania State University Press, University Park, PA, 2015), at p. 50.
- 13 Lüthy, *op. cit.* (note 11), p. 2.
- 14 See *ibid.*, p. 15; Robert Boyle, 'Experiments and considerations touching colours', in *The works of Robert Boyle* (ed. Michael Hunter and Edward B. Davis) (Pickering & Chatto, London, 1999), vol. 4, p. 40; Isaac Newton, 'Hypothesis concerning light and colour', in *The history of the Royal Society of London* (ed. Thomas Birch) (London, 1757), vol. 3, p. 303.
- 15 Henry Power, *Experimental Philosophy, in Three Books: Containing New Experiments Microscopical, Mercurial, Magnetical* (London, 1664), sig. C2v.
- 16 Hooke, *op. cit.* (note 1), sig. B2v.
- 17 *Ibid.*
- 18 See, for instance, Stephen Gaukroger, *The emergence of a scientific culture: science and the shaping of modernity, 1210–1685* (Clarendon Press, Oxford, 2006), ch. 10.
- 19 Hooke, *op. cit.* (note 1), sig. F2r.
- 20 *Ibid.*
- 21 Albert van Helden, 'The telescope in the seventeenth century', *Isis* **65** (1), 38–58 (1974).
- 22 *Ibid.*, at p. 38.
- 23 George Berkeley, *Three dialogues between Hylas and Philonous* (Paquin, Chicago, 1962), p. 27.
- 24 Christoph Lüthy, 'Not *what*, but *why* and *how*', in *What is an image?* (ed. James Elkins and Maja Naef), pp. 182–185 (Pennsylvania State University Press, University Park, PA, 2011), at p. 183. For more on epistemic images, see Lorraine Daston and Peter Galison, 'The image of objectivity', *Representations* **40**, 81–128 (1992); Lorraine Daston, 'Epistemic images', in Payne (ed.), *op. cit.* (note 12), pp. 13–35, at p. 18.
- 25 Robert Hooke, 'Microscopium' in *Lectiones Cutlerianae, or a Collection of Lectures: Physical, Mechanical, Geographical, & Astronomical. Made before the Royal Society on several Occasions at Gresham Colledge* (London, 1678), p. 101.
- 26 Hooke, *op. cit.* (note 1), sig. D2v.

- 27 See their letters and replies to one another in *The correspondence of Isaac Newton* (ed. H. W. Turnbull) (Cambridge University Press, 1959), vol. 1, pp. 92, 110 and 171. See also Alan E. Shapiro, 'Skating on the edge: Newton's investigation of chromatic dispersion and achromatic prisms and lenses', in *Wrong for the right reasons* (ed. Jed Z. Buchwald and Allan Franklin), pp. 99–125 (Springer, Dordrecht, 2005).
- 28 Isaac Newton, 'Mr Isaac Newtons Answer to some Considerations upon his Doctrine of Light and Colors', *Phil. Trans. R. Soc. Lond.* **7**, 5084–5103 (1672), at p. 5085.
- 29 See Brian Gee, *Francis Watkins and the Dollond telescope patent controversy* (ed. Anita McConnell and A. D. Morrison-Law) (Ashgate, Aldershot, 2014); Richard Sorrenson, 'Dollond & Son's pursuit of achromaticity, 1758–1759', *Hist. Sci.* **39** (1), 34–55 (2001).
- 30 See A. I. Sabra, *Theories of light from Descartes to Newton* (Oldbourne Press, London, 1967), pp. 85–91 and 251–263.
- 31 Robert Hooke, 'Critique of Newton's Theory of Light and Colours' in Birch, *op. cit.* (note 14), p. 12.
- 32 René Descartes, *Discourse on Method, Optics, Geometry, and Meteorology* (tr. Paul Olscamp) (Hackett, Indianapolis, IN, 2001), discourse 8.
- 33 Fokko Jan Dijksterhuis, 'Constructive thinking: a case for dioptrics', in *The mindful hand: inquiry and invention from the late Renaissance to early industrialisation* (ed. Lissa L. Roberts, Simon Schaffer and Peter Dear) (Koninklijke, Amsterdam, 2007), p. 60. See also D. Graham Burnett, 'Descartes and the hyperbolic quest: lens making machines and their significance in the seventeenth century', *Trans. Am. Phil. Soc.* **95** (3), i–viii and 1–152.
- 34 For Reeve see Simpson, 'Richard Reeve—the "English Campani"', *op. cit.* (note 9), p. 358.
- 35 'An Account of the Invention of Grinding Optick and Burning-Glasses, of a Figure Not-Spherical, Produced before the Royal Society', *Phil. Trans. R. Soc. Lond.* **3**, 631–632 (1668), parentheses added.
- 36 Van Helden, *op. cit.* (note 21), pp. 45–46.
- 37 Hooke, *op. cit.* (note 1), sig. D2v.
- 38 *Ibid.*, sig. E1r.
- 39 Van Helden, *op. cit.* (note 21), pp. 45–46.
- 40 Hooke, *op. cit.* (note 1), sigs E1v–E2r.
- 41 He built a device for measuring the refraction of various media too: Hooke, *op. cit.* (note 1), sigs E2v–F1r.
- 42 Robert Hooke, 'The Uses and Advantage of Microscopes', Royal Society Library, Classified Papers 20/84 (1693).
- 43 Hooke, *op. cit.* (note 1), sig. F1v.
- 44 Michael Hunter, Antonio Clericuzio and Lawrence M. Principe, *The correspondence of Robert Boyle*, Hooke to Boyle, 3 July 1663 (Pickering & Chatto, London, 2001), vol. 2, p. 98.
- 45 *Ibid.*, Hooke to Boyle, 21 November 1664, p. 364.
- 46 Hooke, *op. cit.* (note 1), sig. F1v.
- 47 Ofer Gal, *Meanest foundations and nobler superstructures. Hooke, Newton, and the 'Compounding of the Celestiall Motions of the Planetts'* (Kluwer, Dordrecht, 2002), p. 50.
- 48 Hooke, *op. cit.* (note 25), pp. 98–99.
- 49 *Ibid.*, p. 98.
- 50 *Ibid.*, p. 99; Robert Hooke, 'Hooke folio', Royal Society MS 847, f. 96. Leeuwenhoek was the most prolific simple microscope user, but even after death he was secretive about his instruments. Although he left some to the Royal Society, even then he probably withheld his best instruments. See Henry Baker, 'An Account of Mr. Leeuwenhoek's Microscopes', *Phil. Trans. R. Soc. Lond.* **41**, 503–519 (1739).
- 51 Hooke, *op. cit.* (note 25), p. 97.
- 52 Hooke, *op. cit.* (note 1), sig. F1v; *op. cit.* (note 25), p. 97.
- 53 Hooke, *op. cit.* (note 25), p. 96.

- 54 Descartes, *op. cit.* (note 32), p. 120.
- 55 Hooke, *op. cit.* (note 1), sig. F2r.
- 56 Hooke, *op. cit.* (note 25), p. 101.
- 57 Hooke, *op. cit.* (note 1), sig. E1r.
- 58 *Ibid.*, sig. E1r.
- 59 Latham and Matthews, *op. cit.* (note 3), 13 August 1664, p. 240. For more on the scotoscope see R. H. Nuttall, 'That curious curiosity: the scotoscope', *Notes Rec. R. Soc. Lond.* **42**, 133–138 (1988).
- 60 Hooke, *op. cit.* (note 1), sig. E1r.
- 61 See Robert Hooke, *Lampas: or, Descriptions of some Mechanical Improvements of Lamps and Waterpoises* (London, 1677).
- 62 Hooke, *op. cit.* (note 25), p. 91.
- 63 Hooke, *op. cit.* (note 1), sig. F2r.
- 64 Hooke, *op. cit.* (note 42), f. 4.
- 65 See, for example, Hooke, *op. cit.* (note 1), sig. F1v; *op. cit.* (note 25), p. 92; Birch, *op. cit.* (note 14), p. 349.
- 66 Hooke, *op. cit.* (note 1), sig. F2v.
- 67 Meghan C. Doherty, 'Discovering the "true form:" Hooke's *Micrographia* and the visual vocabulary of engraved portraits', *Notes Rec. R. Soc.* **66**, 211–234 (2012); Matthew C. Hunter, *Wicked intelligence* (University of Chicago Press, 2013), ch. 1.
- 68 Jim Bennett, 'The social history of the microscope', *J. Microsc.* **155** (3), 167–280 (1989).
- 69 Marian Fournier, *The fabric of reality: microscopy in the seventeenth century* (Johns Hopkins University Press, Baltimore, MD, 1996), pp. 34–39.
- 70 Margaret Cavendish, *The Description of a New World, Called the Blazing World*, 2nd edn (London, 1668), p. 32. Francis Bacon made a related criticism of the microscope: see his *Novum Organum*, book 2, aphorism 39, in *The Oxford Francis Bacon* (ed. Graham Rees and Maria Wakely), vol. 11, p. 345 (Oxford University Press, 2004).
- 71 Hooke, *op. cit.* (note 25), p. 99.
- 72 Hooke, *op. cit.* (note 1), sig. F2v.
- 73 Hooke, *op. cit.* (note 25), p. 82. Leeuwenhoek's letter is reproduced by Hooke in this same lecture. The following events are patched together from Hooke's minutes published in Birch's *History*, extra meeting information omitted from Birch but in the Hooke folio, Royal Society MS 847, and Hooke's later recollections in his lecture 'Microscopium' (*op. cit.* (note 25)).
- 74 Ian Hacking, 'Do we see through a microscope?', in *Images of science: essays on realism and empiricism* (ed. Paul Churchland and Clifford A. Hooker), pp. 133–153 (University of Chicago Press, 1985), at p. 138.
- 75 Latham and Matthews, *op. cit.* (note 3), 13 and 14 August 1664, vol. 5, p. 241.
- 76 Hunter *et al.*, *op. cit.* (note 44), Hooke to Boyle, 28/29 October 1664, p. 371.
- 77 Hacking, *op. cit.* (note 74), p. 138.
- 78 Hooke, *op. cit.* (note 25), p. 93.
- 79 Birch, *op. cit.* (note 14), p. 347; Hooke, *op. cit.* (note 25), pp. 82–83.
- 80 See, for instance, his letter to the Royal Society of October 1676: after making estimates of the size and quantity of the tiny animacula, he writes 'the make of the Microscopes, employed by me, I cannot yet communicate.' Antoni van Leeuwenhoek, 'Monsieur Leewenhoek's Letter to the Publisher, Wherein Some Account is Given of the Manner of His Observing So Great a Number of Little Animals in Divers Sorts of Water, as was Deliver'd in the Next Foregoing Tract: English'd out of Dutch', *Phil. Trans. R. Soc. Lond.* **12**, 844–846 (1677), at p. 845.
- 81 This is according to the minutes in Birch, and despite the fact that he implies it was pepper water in 'Microscopium' (*op. cit.* (note 25)). On a couple of occasions Birch's and Hooke's later recollections do not match. I have tended to follow the minutes, which at this time, post-Oldenburg, were in any case taken by Hooke.
- 82 Birch, *op. cit.* (note 14), pp. 346–347.

- 83 Hooke, *op. cit.* (note 1), p. 47.
- 84 Hooke, *op. cit.* (note 23), pp. 91–95.
- 85 *Ibid.*, p. 91.
- 86 Birch, *op. cit.* (note 14), p. 349. These minutes just say that the mount was highly adjustable. The detail is taken from an account of the following observation (15 November) in the ‘Hooke folio’, Royal Society MS 847, f. 109.
- 87 Birch, *op. cit.* (note 14), p. 349.
- 88 *Ibid.*, p. 347.
- 89 See especially Steven Shapin, *A social history of truth: civility and science in seventeenth-century England* (University of Chicago Press, 1994); Shapin and Schaffer, *op. cit.* (note 10).
- 90 Birch, *op. cit.* (note 14), p. 349.
- 91 Hooke, *op. cit.* (note 25), p. 92.
- 92 Birch, *op. cit.* (note 14), p. 352.
- 93 Hooke, *op. cit.* (note 50), f. 109. The minutes in the Journal Book and published by Thomas Birch end in mid-sentence before the discussion concludes, and even omit the next two meetings. Those in the recovered ‘Hooke folio’ continue. This was not uncommon during the time that Hooke was secretary and providing draft minutes to be written up: see Robyn Adams and Lisa Jardine, ‘The return of the Hooke folio’, *Notes Rec. R. Soc. Lond.* **60**, 235–239 (2006), at p. 238.
- 94 Hooke, *op. cit.* (note 50), f. 109.
- 95 *Ibid.*, f. 112.
- 96 Hooke, *op. cit.* (note 25), p. 92.
- 97 See also Leeuwenhoek’s discovery that many different types of body were made of small globules, and his later realization that these were just apparitions and misleading appearances through his lenses: Harry K. Phinney, ‘A revisionist history of microscopical sciences’, *J. Microsc.* **159** (2), 125–132 (1990), at p. 126.
- 98 Hooke, *op. cit.* (note 1), sig. F2v.
- 99 Doherty, *op. cit.* (note 67).
- 100 Samuel Y. Edgerton Jr, ‘Galileo, Florentine ‘Disegno’, and the ‘Strange Spottednesse’ of the Moon’, *Art J.* **44** (3), 225–232 (1984).
- 101 Mario Biagioli, *Galileo’s instruments of credit: telescopes, images, secrecy* (University of Chicago Press, 2006), p. 148.
- 102 Hooke, *op. cit.* (note 1), p. 207.
- 103 The description of his appearance comes from the introduction to Richard Waller (ed.) *The posthumous works of Robert Hooke* (London, 1705). Waller’s ‘grey’ eyes are probably what we would these days call blue, as Leah Marcus has discussed (and Rita Angus’s recent portraits of Hooke depict): Leah Marcus, *Unediting the Renaissance: Shakespeare, Marlow and Milton* (Routledge, London, 1996), p. 12. For more on Hooke’s appearance, see Lisa Jardine, *The curious life of Robert Hooke: the man who measured London* (Harper Collins, New York, 2003), pp. 15–19, and William B. Jensen’s response: ‘A previously unrecognised portrait of Joan Baptista Van Helmont (1579–1644)’, *Ambix* **51** (3), 263–268 (2004).
- 104 Hooke, *op. cit.* (note 1), p. 207.
- 105 Janice Neri, ‘Some early drawings by Robert Hooke’, *Arch. Nat. Hist.* **32** (1), 41–47 (2005). See also Janice Neri, ‘Between observation and image: representations of insects in Robert Hooke’s *Micrographia*’, in *The art of natural history: illustrated treatises and botanical paintings, 1400–1850* (ed. Therese O’Malley and Amy R. W. Meyers), pp. 83–108 (National Gallery of Art, Washington DC, 2008); Hunter, *op. cit.* (note 67), pp. 125ff. The notebook is preserved as British Library Add. MS 57495.
- 106 Neri plausibly suggests that Hooke was relying on his memory to serve him with a date when writing the creature’s description for the book. (For an estimation of Hooke’s leaky memory, see John Aubrey, *Brief Lives, chiefly of contemporaries, set down by John Aubrey between*

- the *Years 1669–1696*, vol. 1 (ed. Andrew Clark) (Clarendon Press, Oxford, 1898), p. 411.) The images in *Micrographia* are the work of an engraver, using master drawings that Hooke provided. (Only one of these master drawings is known still to exist, as Royal Society Classified Papers 20/7: ‘figures frozen in urine’. See Harwood, *op. cit.* (note 4), pp. 126–127.) It seems that Hooke did not have the draft with him after making the master drawing. Neri found it in John Covell’s ‘Natural history and commonplace notebook’, where it has resided at least since Covell gave the book to James Pettiver some time probably in the 1680s, although how Covell came by it is unknown: Neri, *op. cit.* (note 105), p. 46.
- 107 Quoted in Neri, *op. cit.* (note 105), p. 47, fn. 3.
- 108 Quoted in *ibid.*, p. 46.
- 109 Hooke, *op. cit.* (note 1), p. 204.
- 110 *Ibid.*, sig. E1r.
- 111 Edward G. Ruestow, *The microscope in the Dutch Republic: the shaping of discovery* (Cambridge University Press, 1996), p. 151. See also Hooke’s schemes of a long-legged spider, which loses four legs between being observed from above and from below: Hooke, *op. cit.* (note 1), opposite p. 198.
- 112 Ruestow, *ibid.*
- 113 Baker, *op. cit.* (note 50).
- 114 Fournier, *op. cit.* (note 69), p. 34; Gerard L’E. Turner, ‘The impact of Hooke’s *Micrographia* and its influence on microscopy’, in *Robert Hooke and the English Renaissance* (ed. Paul Kent and Allan Chapman), pp. 124–145 (Gracewing, Leominster, 2005); Henry Baker’s works included *The Microscope Made Easy* (1743) and *Employment for the Microscope* (1753); George Adams wrote *Essays on the Microscope* (1787).
- 115 Relatedly, when Uffenbach visited the Royal Society’s repository after Hooke’s death, he was horrified by the Society’s inability to maintain objects in any sort of condition that allowed them to be inspected after the initial interest in them had passed. See Hunter, *op. cit.* (note 67), p. 168.
- 116 Neri, *op. cit.* (note 105), p. 44. Three drafts are marked: ‘R.G. being present’, ‘D.C. being present’, ‘E.T. Ocul. Testis’. Neri has suggested Ralph Greatorex as a candidate for R.G., and in private communication Stephen Gaukroger has suggested to me that D.C. could be Daniel Colwall.
- 117 Neri suggests that Hooke was particularly influenced by Willem Piso’s *Historia Naturalis Brasiliae* (1648): Neri, *op. cit.* (note 105), p. 98.
- 118 Robert Hooke, ‘An Instrument of Use to take the Draught, or Picture of any Thing, Communicated by Dr. Hook to the Royal Society, Dec. 19, 1694’, in *Philosophical Experiments and Observations of the Late Eminent Dr. Robert Hooke, S.R.S. and Geom. Prof. Gresh and Other Eminent Virtuoso’s in his Time* (ed. William Derham), pp. 292–296 (London, 1726), at p. 294.
- 119 Lorraine Daston, *op. cit.* (note 24), p. 18.
- 120 Biagioli, *op. cit.* (note 101), p. 145.
- 121 Hooke, *op. cit.* (note 1), sig. A2v.
- 122 Daston, *op. cit.* (note 24).
- 123 For Wren, see Jim Bennett, *The mathematical science of Christopher Wren* (Cambridge University Press, 1982), p. 73. That they collaborated and learned from one another can be inferred from various similarities. For example, Matthew Wren writes about a ‘Mathematician’ member of the Oxford group (surely cousin Christopher) who invented a way of measuring the magnification of a microscopical image, and Hooke describes such a method in his preface: Matthew Wren, *Monarchy Asserted or the State of Monarchicall & Popular Government...* (Oxford, 1659), sig. A8r; Hooke, *op. cit.* (note 1), sig. F1r.
- 124 Martin Kemp and Nathan Flis, ‘Mapping the cerebral globe’, *Nature* **456**, 174 (2008).
- 125 Thomas Sprat, *The History of the Royal Society of London, for the Improving of Natural Knowledge* (London, 1667), p. 316.