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CHAPTER THIRTY-SIX

Microscopes

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The microscope is one of the truly emblematic tools of science. The familiar image of a "scientist at work" will inevitably feature a white lab coat (conveying disinterested authority), and a microscope on the lab bench: a sign of diligence, of control over nature, and access to hidden worlds. Yet, unlike its close relative the telescope, the microscope's role in the history of science is uncertain. The question of its origins is vexed, and its early use is typically seen as desultory. After initial fumblings (so the standard accounts relate) came a period of great achievement—that of Robert Hooke, Antoni van Leeuwenhoek, Marcello Malpighi, and Jan Swammerdam. But once this golden age was over we supposedly return to futility: microscopy in the eighteenth-century has been labeled "fallow, scientifically" (Turner 1980, 161). The modern age of microscopy then appears *ex nihilo* with the invention of lenses fully corrected for the various aberrations that hinder clear vision.

My main purpose in this chapter is to provide an alternative to this narrative, emphasizing continuity where others have seen startling change; interweaving stories—of popularization, discovery, trade, invention and theory—that others have seen as separate. This is not done to downplay the achievements of Hooke, Lister *et al.*, rather to set those in their proper context and give better shape to the history of what remains a vitally important scientific instrument. The chapter is laid out chronologically—however I make only preliminary suggestions for a history of the microscope in the twentieth century, a project for which the foundations have not even been laid at present.

Origins

The microscope, as one historian has wryly commented, was "never invented" (Lüthy 1996, 2). Objects appear larger through water or uneven pieces of glass—surely we cannot talk of the origins of magnification. The development of lens-grinding, meanwhile, had nothing to do with the systematic study of the very small; rather, its concern was providing aids to defective vision. If we think of a microscope as an instrument for

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studying minutiae, we could start with Giovanni Rucellai, who is said to have made drawings of a bee in an enlarging mirror in 1523 (Ronchi 1970, 107). But his work was dismissed as either illusion or magic, and has escaped the notice of most historians. Instead, accounts of the microscope's early years have tended to begin with the recognizably modern *instrument*, that is, the particular arrangement of lenses connected by a cylindrical tube that was first contrived in the Low Countries in the years around 1600—perhaps the work of the same craftsmen who invented the telescope (Turner 1985).

For the first half-century of the microscope's use we have a rather fragmented picture. We know of a handful of early pioneers, who elaborated on the basic two-lens system and invented new stands, and we know that these instruments circulated around Europe along routes of courtly exchange (Fournier 1996). The main use in these early years was entomological: Galileo examined "a certain insect in which each eye was covered with a rather thick membrane"; French *savant* Nicolas-Claude Fabri de Peiresc set the tone for early modern microscopic interpretation when his investigations into fleas and lice led him to celebrate the "effects of divine providence, which was far more incomprehensible to us when that aid to our eyes was wanting" (as quoted in Fournier 1996, 25). In Rome, the first microscopic illustrations were published, showing the exterior parts of the bee and titled *Melissographia* (1625).

Soon, dissection was added to observation, and internal structures were described. For example, Giovanni Battista Odierna, a Sicilian priest, made a major advance when he dissected the eye of the fly and speculated on the mechanism of perception. Here we have one of the first instances of microscopic observation playing a role in natural explanation. In England, under the banner of Baconianism, this was taken a step further, and made into a more programmatic (if idealized) project. Not only was there Bacon's general claim that it would be "by instruments and helps that the work is done," but, further, Solomon's House would be replete with "Glasses and Meanes to see the small and Minute Bodies, perfectly and distinctly: As shapes and Colours of Small Flies and Wormes, Graines and Flawes in Gemmes which cannot otherwise be seen, Observations in Urine and Bloud not otherwise to be seen" (as quoted in Wilson 1995, 50).

Gradually, the microscope was deployed in new disciplines: botany, mineralogy, and the anatomy of higher organisms. In mid-century England, for example, two important works advocated the use of microscopes in embryological research. These were Nathaniel Highmore's *History of Generation* (1651), which makes casual mention of the microscope in answering the question of whether the embryo chick develops first in the yolk or the white of the egg, and William Harvey's *Exercitationes de generatione animalium* (1651), which encourages the use of "Perspectives" in the same connection.

In a century of high rhetoric, the microscope was quickly and eloquently brought into line with the dominant physico-theological justification of natural inquiry. This project, of "reading in the features of the world the existence, presence, and characteristics of a supernatural being" (Wilson 1995, 176), functioned not only as an apologia for natural philosophy, but also as a guarantor of objectivity—albeit one quite distant from later and more familiar paradigms that prize procedure and verisimilitude over baroque verbiage. This justification for microscopy developed in tandem with an involuted notion of the link between the eye of the observer, the nature of the microscope itself, and the eye as an object of inquiry. This was just the combination that Odierna had begun research into in the 1640s, and it was to become one of the enduring subjects of microscopical research, with developments in microscopy and optical theory alike refining the geometrical and anatomical understanding of vision (Schickore 2007).

Practically, too, microscopy was on the rise across Europe. The expert skill required to make small highly convex lenses was now relatively widespread, with centers of production in all the major capitals.

Hooke and After

It was in this context—of high speculation and growing craft knowhow—that Robert Hooke first embarked on his famous microscopical researches. These were begun in 1663 as a series of demonstrations to the Royal Society, for whom Hooke was Curator of Experiments.

Preparing his samples of moss, cork, mold, vinegar and flint fully occupied even Hooke's great experimental talents. In spite of the excitement the microscope was beginning to generate, there was almost no protocol for the preparation and mounting of specimens, method of illumination, configuration of lenses or sharing of results. Indeed, the nature of the microscope itself was up for grabs, with Hooke writing that he had experimented with "a Microscope with one piece of Glass [...] another only with a plano-concave [...] others of Waters, Gums, Resins, Salts, Arsenick, Oyls, and with divers other mixtures of watery and oyly Liquors" (Hooke 1665, unpaginated preface). But in the main Hooke worked with an instrument purchased from the London tradesman Christopher Cock: a large microscope that could be used with two or three lenses, which he had adapted with various devices for mounting and viewing the specimen (Clay and Court 1932, 20–31).

For Hooke, as for so many who followed, illumination was the main problem. Sitting at his south-facing window, there was often insufficient light—but then suddenly there could be too much, putting the specimen at risk of incineration. In this case Hooke either inserted a sheet of greased paper between the condensing lens and the specimen or reflected the light via a sanded mirror. Artificial illumination was also possible, and here Hooke constructed an elaborate system using an oil lamp and two condensing lenses.

This serves to remind us how complicated and strenuous observation could be—after all, Hooke had constructed this set-up in order to avoid using single lenses, which, though powerful, were difficult to grind and had to be pressed almost onto the surface of the eye. In addition, the practice of microscopic manipulation itself was a key part of Hooke's natural philosophy, not merely as a precursor to observation but as an active part of observation itself. As Hooke explained, his "usual manner" of examination involved "varying the degrees of light and altering [the specimen's] position to each kinde of light" in order to reveal details of physical structure. In his description of the eye of a fly, for example, Hooke noted the different structures (apparently) visible under different kinds of light. This is Hooke as the true mechanical philosopher, drawing no distinction between manipulation, mechanism, and "Philosophical Inquiry," and indeed critiquing his contemporaries on the grounds of their limited instrumental procedures (Bennett 1986).

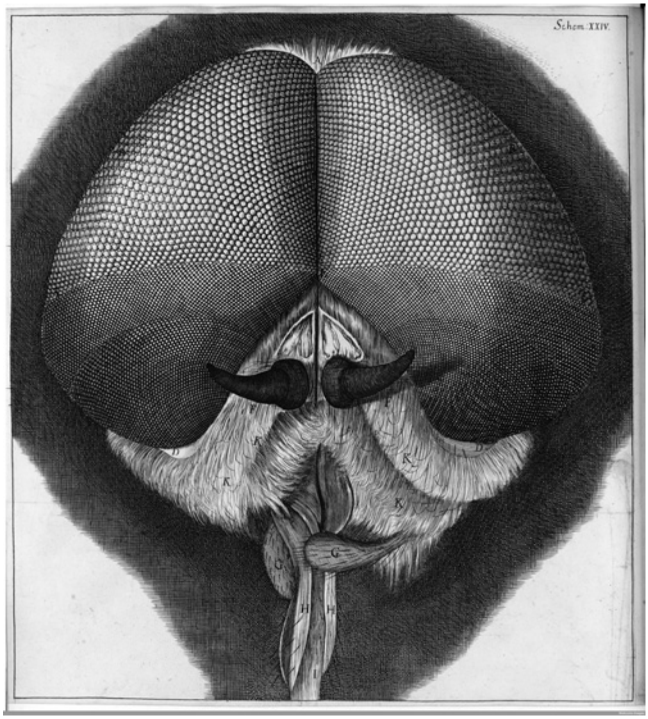

Figure 36.1 "Eyes and head of a grey drone fly," plate XXIV from Hooke's *Micrographia* (1665, facing p. 175). Wellcome Library, London.

The labor was worth it. On 6 July 1663 Hooke was ordered to prepare his observations for publication. In only eighteen months he had overseen the production of *Micrographia* (1665), the undoubted masterpiece of early microscopical research, containing large folding plates, stunningly engraved with fleas, fungi, plants, needles and spiders (Figure 36.1). These, of course, are not simply an embellishment: one of Hooke's main difficulties was how best to share his observations—a question of great importance throughout the history of microscopy (Taub 1999, 732). Even if the preparation and lighting could be managed so that each of his colleagues at the Royal Society could see through the instrument (no mean feat), the multitude of observations that went into the analysis of each specimen—through different arrangements of lenses, for example—could not be repeated in full. So the engravings, which captured this multitude of views, *were* the observations. And what they revealed was remarkable: amongst the welter of insights and speculations Hooke gave the first description of micro-fungi and adopted the word "cell" to describe constituents of cork. He had demonstrated, for the first time, that the microscopic world was various and strange enough to require examination in its own right, rather than as a mere adjunct to the established disciplines.

Inspired by Hooke's work, others soon added to the list of microscopic discoveries. By far the most dramatic of these came from an unknown Dutchman named Antoni van Leeuwenhoek, who truly set out to map the "new discovered world" that Hooke had begun to describe. Using lenses that could magnify more than 250 diameters, Leeuwenhoek was the first to see spermatozoa, bacteria, blood cells and a veritable zoo of microorganisms, which he called "animalcules."

The case of Leeuwenhoek brings out perhaps the most important aspect of early microscopy: credibility. Leeuwenhoek's discoveries were remarkable, to be sure, but could his reports be trusted? He was a respectable member of Delft society, and in gaining the respect of the members of the Royal Society he took a huge step towards more general acceptance. But the latter was hard-won, even in his own country. Leeuwenhoek's technique for making lenses was a closely guarded secret and his skill in preparing specimens was formidable, so he went to the extraordinary length of opening his house and making special demonstrations for visitors. Two anecdotes give a sense of the drama and labor of Leeuwenhoek's practice: on one occasion he reported spending days killing over one hundred mosquitoes in order to prepare an observation of the insect's mouth-parts; on another the artisan-scholar Nicholas Hartsoeker accosted Leeuwenhoek on the latter's doorstep in order to grill him over the impossibility of dissecting a flea without obscuring the light with the knife (Ruestow 1996, 151–3). Long-range communication was perhaps easier for the harried Leeuwenhoek. In order to keep the Royal Society onside he even prepared specimens, sending them attached to his letters; eventually he donated over 200 microscopes, a necessary step given that Leeuwenhoek's manner of working was effectively to build an entire system—specimen and microscope fixed together—for each separate observation.

For Leeuwenhoek's contemporaries on the continent it seems that, like the pre-*Micrographia* researchers in England, discussion of optics and instrumental set-ups was not deemed relevant when it came to publishing results. Here, clearly, other measures of authenticity were being used. For example the Bologna-based Royal Society correspondent Marcello Malpighi, in developing an extremely ornate explanation of living processes based on his observations of microscopic tubes and pores (most notably the capillaries), provided almost no information on the instruments he used—the quality of his observations seemingly transcending the need for the kind of extensive instrumental digressions given by Hooke. Far less urbane, but just as prolific, the Dutch entomologist Jan Swammerdam began a remarkable series of studies in insect physiology; while in England Nehemiah Grew pioneered the microanatomy of plants.

These projects, remarkable in their scope as they may seem, were not at the time considered uniformly successful. Grew and Malpighi, for example, failed to find organs and systems in plants analogous to those in animals; Swammerdam struggled throughout his life against his father's wishes that he return to medicine, and against his own crises of faith in experimental philosophy as a means of spiritual fulfilment. Most dramatically of all, the virtuosi—and in particular their researches into the very small—were pilloried on the stage and in satirical poems (Nicolson, 1956). Towards the end of the century, harassed by the playwrights and witnessing a decline in microscopical research, Hooke lamented that he knew "of none that make any other Use of that Instrument, but for Diversion and Pastime" (as quoted in Wilson 1995, 226).

The Development of the Instrument Trade

It is perhaps not surprising, therefore, that if we follow traditional accounts we find the microscope in poor health *circa* 1700. Historians have typically taken Hooke's pronouncement at face value. Hooke himself had set the microscope aside in favor of other researches; Leeuwenhoek's immense productivity was soon to dwindle, and with Swammerdam and Malpighi both dead, the instrument's champions would seem to be few. And yet, looked at from another, perhaps less lofty vantage point, this supposedly "fallow" period in the microscope's history is transformed—for it is at precisely the turn of the eighteenth century that the popular use of the instrument began.

To understand this transformation it is necessary to look in some detail at the optical instrument trade *circa* 1700. In England, artisans were struggling free of the guild system, which in principle defined who could trade and what they could offer. Meanwhile, the clientele for those selling microscopes was diverse, ranging from fellow artisans all the way to royal appointment. Also important, in instrument manufacture as elsewhere, was the increasing division of labor. Where the first instrument makers—just over a century prior—were highly specialized, working each piece from beaten brass to divided scale, the new breed would put their name to an instrument assembled from parts made elsewhere. A microscope, for example, required expert lens-grinding, tube manufacture and stand construction, and these three functions were by no means all carried out by the "maker" whose name appeared on the finished product.

So just as the scholar Hooke could lament that the microscope was becoming otiose, an entrepreneur like James Wilson could boast that "The Use of Microscopes is so well known, that it's as needless to attempt their Recommendation to the Inquisitive, as it would be tedious to numerate their particular advantages in Natural Inquiries" (Wilson 1702, 1241). With these words Wilson introduced the new portable "screw-barrel" microscope to the English market—and though the patter of the marketplace may be in evidence, Wilson was not merely aiming for popular appeal. The context of his essay—the Royal Society's *Philosophical Transactions*—speaks of the complex interrelation of scholarship and commerce in the period. Indeed, as he continues Wilson deftly adds a touch of drama to Hooke's physico-theology, writing of the "entertainment" of confirming the superiority of natural objects over "the most Celebrated pieces of Art" (Wilson 1702, 1241).

Here Wilson evokes a point Hooke had made in *Micrographia*, doing so for an audience who would understand the reference, in order to justify the development and marketing of a cheap microscope that would allow repetition of experiments first published over a quarter of a century earlier. And the design advocated by Wilson—an elegant single-lens microscope that packed neatly into a small case—proved immensely successful.

While microscopes of Hooke's design had been used by a handful of specialists across Europe, now portable microscopes were sold in their hundreds, at prices that made them accessible to the large number of interested amateurs. We might usefully compare this situation with the near-contemporary rise in the popularity of pocket globes—just like the portable source of microscopic knowledge, a portable source of geographic knowledge catered to a rapidly growing market for polite learning. Wilson's pocket microscope was soon offered by a large number of opticians and instrument makers, almost always sold with a pre-prepared selection of slides and apparatus for viewing the very paradigm of microscopic achievement, the circulation of the blood (normally in the tail of a small fish encased in a narrow vessel) (Figure 36.2).

So Hooke's words were highly prescient—indeed one of his charges against the microscope was that it was merely "a portable Instrument, and easy to be carried in one's pocket." Far from being a fall from grace, as Hooke would have it, the

Figure 36.2 A screw-barrel microscope made to James Wilson's design, with a variety of lenses and slides. Wellcome Library, London.

development and marketing of cheaper instruments across Europe constituted a remarkable success for the new experimental philosophy.

Each country—even each region—saw subtle differences in the economy of knowledge production and circulation. For example, Wilson's microscope was depicted fully assembled in the *Philosophical Transactions*, so that a potential user would have to go direct to the instrument maker. In France, Louis Joblot proposed a microscope of very similar design, whose illustration was a technical one showing the separate parts of the microscope, the intention being to allow any interested researcher to construct their own instrument (Ratcliff 2009, 22). In the German lands, meanwhile, highly ornate instruments were being made by artisans like G. F. Brander alongside so-called "toy" wooden microscopes; in Italy optical know-how was often in the hands of amateurs, sometimes learned priests.

Amongst those who benefited directly from the new popular microscopy was Edmund Culpeper (c. 1670–1737), the instrument-maker who most successfully exploited the design Wilson had introduced. Trading under the sign of the Cross Daggers at the "Old Mathematical Shop" in Moorfields, London, Culpeper was the son of an Oxford-educated clergyman and was apprenticed to the mathematical instrument-maker Walter Hayes. Through his father's college, Merton, he may have had contact with some of the savants who resided there. Operating quite literally on the borders of the city of London's guild system and clearly a master craftsman, Culpeper took what would have seemed to his contemporaries a drastic step, away from a strictly mathematical range of instruments and into the marketing and manufacture of optical and "philosophical" instruments (Turner 1980, 9–11; Bennett 2011, 703).

Culpeper first experimented with the incorporation of the simple microscope into an all-purpose compendium, but he quickly saw the possibilities of Wilson's smart design. With his background primarily in the engraving of scales and delineation of sundials, it is highly likely that Culpeper collaborated with a lens-maker, perhaps Wilson himself. He had competition in the manufacture of single-lens microscopes from Edward Scarlett, and elsewhere in the capital John Marshall and a few others offering compound microscopes largely derived from Hooke's design. So Culpeper was opportunistic, versatile and dismissive of the trade restrictions that ought to have limited his output in both size and range—in all of these respects he was a pioneer, both creating and catering to a new market for mathematical *and* philosophical education amongst a growing bourgeoisie.

The scientific enterprise of the Enlightenment was as much a matter of commerce, spectacle, and politics as it was one of discovery and invention—and this in no way diminishes its importance with regard to what went before and what came after. The new breed of popular lecturers also made extensive use of the microscope, adding sublime rhetoric to the physico-theological patter and developing instruments that facilitated group viewing.

Microscopy in this period was not a self-contained and discipline-bound practice, but rather part of a Europe-wide culture of collecting, lecturing and display. Both Leeuwenhoek's and Swammerdam's collections had been on the itinerary of learned tours around Europe, and in England the cultivation of a complete system of philosophical apparatus was an important part of gentlemanly culture. The wide range of types of specimen prepared by microscopists of the time and the marketing of the microscope with other mathematical and philosophical instruments were of a piece, and only make sense in the context of collections of *naturalia* (Taub 1999, 738). Microscopes themselves could constitute, as well as reveal, objects of curiosity. Hence, where historians have tended to emphasize the undoubted decline in the number of microscopical *discoveries* between c.1650 and c. 1750, we ought instead to acknowledge continuity in the rhetoric and display associated with microscopical practice.

By mid-century, the repertoire of microscopical observations was firmly established, not least due to the tireless work of the popular writer Henry Baker, a regular contributor to the *Philosophical Transactions*, and by trade a tutor to the deaf. His most successful book, *The Microscope Made Easy* (1742), drew on the growing market for popular natural philosophy, and the 1000 copies of the first edition sold out in a mere five months. Soon new impressions and then editions were prepared, and the work was translated into numerous languages (Turner 1980, 195). Baker's books are as much about microscope design and manufacture as they are about the natural world. *The Microscope Made Easy* opens with yet another discussion of Wilson's simple microscope, before showing how it can be adapted for tabletop use and turned into a compound instrument. The merits of various other designs are assessed, all of them available from Baker's favored artisan and collaborator John Cuff. Indeed, in spite of Cuff's perpetual financial difficulties, the pair's next collaboration was to be momentous. In preparation for a sequel to *The Microscope Made Easy*, Baker was performing a series of experiments on crystals. Finding that the crude focus mechanism and obstructed stage of the current "Culpeper-type" hindered his research, he worked with Cuff to design a new instrument, in which the body—supported on a side-pillar with a fine-screw focus mechanism—was made entirely from brass, supported on a sturdy wooden base. Though other designs persisted—for example Culpeper's, Wilson's and a new portable "drum" microscope by Benjamin Martin—Cuff's design was highly popular, eventually to become standard; it is recognizably the ancestor of the modern instrument.

Nor were Baker's successes purely in marketing and design: seizing quickly on a report from the Swiss naturalist Abraham Trembley, Baker published a report of his own experiments on the behavior of the "polypes"—waterborne creatures with remarkable powers of regeneration. If these objects of inquiry were new in the eighteenth century, there was much that was continuous with earlier work. For example, echoing Hooke and the earlier microscopists, popular writers of the eighteenth century gave introductions to their works in which the optical system of the eye and the microscope were explained—the wonderment of the earlier writers giving way to an "improving" discourse that at once explained the basics of modern optics and justified the use of the microscope as a mere extension of the senses, no different in kind from our own optical apparatus (Schickore 2007, 21–3). And the nature of the insect eye allowed writers like Benjamin Martin to advance novel theories while maintaining the older metaphysical notion of the perfection of natural optics, or "divine geometry" as he called it. This theorizing, in addition to contemporary debates over spontaneous generation and preformation, and about the division of the plant and animal kingdoms and microanatomy show that microscopical research in this period was in fact a lively enterprise—perhaps undervalued by historians because of an interpenetration of trade, popular exposition and discovery unknown before or since.

In the eighteenth century, then, we see discontinuities with what went before, but they are not of the sort typically identified by historians of the microscope. The microscope was no longer the province of a handful of scholars keen to extol the instrument's virtues. Popular lecturers had taken over; the instrument trade was booming; new designs took the microscope into the field, into the public hall and into the drawing room. The emphasis was now on having a microscope by one of the major makers—the names of Dollond, Adams, Martin, and Cuff signaled quality, though not necessarily any improvement from the previous century in the optics. Sure enough, the initial burst of great discovery was over, but the physico-theology that was developed in the seventeenth century was consolidated and the number of manufacturers grew. As we shall see, these were vital for the rapid expansion of microscopy that was to come.

The Microscope in the Nineteenth Century

At the turn of the nineteenth century, a naturalist wishing to investigate insects, polyps or the circulation of the blood could choose from a vast range of instruments. Nor were these only the large new stands designed by the various makers. Because the compound microscope was known to exacerbate the problems of aberration, the simple microscope remained extremely popular. In addition, the growing enthusiasm for natural history in the second half of the eighteenth century led to new designs of single-lens instrument, notably the folding portable design associated with the botanist William Withering and John Ellis's "aquatic" microscope, in which a small vessel replaced the stage and water-borne microorganisms could be observed in their natural environment.

These more private pursuits were matched in the public sphere by the microscopy on offer in the "shows of London" (Altick 1978). The solar and lucernal microscopes, popularized in the second half of the eighteenth-century, projected an enlarged image onto a wall and therefore allowed collective viewing of microscopic phenomena. Drawing room demonstrations had given way to spectacular shows, first conducted by itinerant lecturers like Benjamin Martin, and then installed into the capital's "exhibitions", for example that hosted by Gustavus Katterfelto, whose "wonders" included insects "as big as birds". Even as late as 1839 the proprietor of the Colosseum at Marylebone, John Braham, could breathlessly (and of course impossibly) boast of magnifications of over 4.6 million times (Altick 1978, 83–5, 152).

But at the same time, other sorts of demonstrations were taking place. Amateur enthusiasts were gathering informally to discuss all manner of "philosophical" subjects, and microscopy was a major part of the trend. Gentlemanly meetings often used the same techniques as the larger public shows—giant diagrams and projecting microscopes—but the tone was of learned pleasure rather than raucous spectacle. In many ways the microscope was a model instrument of self-improvement, combining fieldwork, dexterous preparation, artistic skill and patience, and the knowledge of classificatory schemes. Instruments, drawings and slide arrangements were compared, and perplexing discoveries debated. The more refined enthusiasts could choose from a wide range of table-top instruments, most of them set up to work with both simple and compound configurations, some with multiple eyepiece tubes to facilitate collective viewing.

It is important to note that this amateur, semi-private microscopy was the cutting edge of practice in Britain—but elsewhere the microscope was a tool of the nascent laboratory. Experimental physiologists like Johannes Müller made extensive use of the microscope, in particular in his researches into blood globules and the development of the embryo. As Jutta Schickore has shown, microscopy in the German lands was, in this period, fully compatible with the *Naturphilosophie* tradition of self-experiment, and with the view that the experimental set-up bridged the epistemological gaps opened by Immanuel Kant's transcendental idealism (Schickore 2007). In spite (or perhaps because) of the excellent lenses being developed on the continent at this time, assessment of the microscope's performance was secondary to the careful cultivation of experimental skill.

National differences in experimental style were marked throughout the nineteenth century, and yet instruments and texts could move freely. Henry Baker's work, mentioned above, was cited as authoritative well into the nineteenth century in France and Germany, and competition was intense between the main firms of Chevalier (France), Amici (Italy), Fraunhofer (Germany) and the numerous manufacturers working in London. As rivalries between instrument-making firms deepened and extended to matters of international competition, designs proliferated. Nor were practitioners unaware of the problems that such a fractured market could cause. How were observations to be verified when two quite different kinds of microscope might be in use? How were the merits of simple *versus* compound instruments to be decided? There were, of course, lofty imperatives, largely unchanged from the preceding century: having a good instrument from an established maker was a prerequisite, moral standing remained important, and speculation was to be avoided. And yet standards of comparison—of lenses, specimen preparation and observational practice—were few and far between. In this context, new theories generated lively controversy, which eventually turned to matters of technique.

The "globular" theory, for example, was an early nineteenth-century attempt to describe the formation of living tissues (Pickstone 1973; Schickore 2009a). The questions that have vexed historians have concerned the relation of the globular theory to cell theory, and the reasons for its demise—generally taken to be linked to improvements in microscopy. Yet what is important here is not so much the success or failure of the theory itself, rather the attention it drew to the importance of comparative standards in microscopical work. How could theories about the importance of microscopic objects be debated when estimates of their size varied so wildly? It was in this context, of collaborative witnessing and debate over the ultimate constituents of living tissue, that a key technology was developed: the test object.

This innovation in microtechnique was primarily the work of Charles Goring, an Edinburgh-trained physician who had—in an age increasingly favoring reliable single-lenses—a "lurking fondness" for the compound microscope. This encouraged Goring to devise methods of comparison of what he termed "penetrating power" (Schickore 2009b). While Goring struggled to establish this terminology, his test objects themselves proved wildly successful. The earliest were the parts of insects that displayed regular patterns, for example the striations on the scales of butterfly wings. Soon the remarkable forms of diatoms were being used instead, and eventually mechanically-ruled gratings were developed by Friedrich Adolf Nobert, these being so fine that attempts to resolve them resulted in dramatic improvements in lens design (Turner 1980, 141–58).

Goring's innovation can be taken as representative of a general move in the early nineteenth century towards a concern with the quality and combinations of different kinds of glass used in microscope lenses. Some instrument-makers—for example Giovan Battista Amici in Modena and John Cuthbert and Andrew Pritchard in London—rejected glass lenses altogether, working with diamond and sapphire, or attempting to make reflecting microscopes on the same principle as the long-established reflecting telescope. But these alternatives were eventually trumped by the work of Joseph Jackson Lister, who collaborated with the instrument-maker William Tulley to make, in 1827, the first lenses corrected for both chromatic and spherical aberration—that is, the distortion of the image owing to variant refraction of different colors, and to the range of focal points across the lens (Turner 1980, 13–15).

Appropriately enough, the first use to which Lister's instrument was put was the observation of blood, carried out with Thomas Hodgkin at Guy's Hospital. In an 1827 paper Lister and Hodgkin critically assessed the globular theory, finding no evidence of the formative particles within blood cells (Bracegirdle 1977). They also provided a comparison of the widely divergent measurements of blood cells with their own estimation, which closely matches modern figures. The authors stated that the instrument was superior even to Amici's reflecting microscope, and that, although faithful to what they had seen, advocates of the globular theory had been misled by defective lenses and preparation techniques.

If the globular theory had been a valiant attempt to make microscopy central to studies of living tissue, it was work done with the new microscopes that proved decisive in the establishment of experimental histology. The paper by Hodgkin and Lister served to reiterate one of the key conclusions of earlier microscopy: namely that there would always be a layer or stage in natural processes inaccessible to experiment. It is not surprising, therefore, that the microscopic paradigm that emerged in this period—the cell theory of Schleiden and Schwann—involved much larger constituent parts than the globular theory. Indeed the most notable work on the nature of the cell in this early phase was done by Robert Brown, who identified and named the nucleus using a single-lens microscope.

Other disciplines, too, were undergoing microrevolutions. For example, research into the question of spontaneous generation took a remarkable turn with the announcement, by Christian Gottfried Ehrenberg in Berlin, that fossilized "infusoria" made up vast swathes of the earth's strata. Where the new *Naturphilosophie* was welcomed, for example at Edinburgh, there was a particular clamor for infusorial research. Elsewhere, amongst the most influential of Ehrenberg's interlocutors was a young Charles Darwin, just back from his voyage on board the Beagle and keen to engage with the new discoveries about infusoria in order to establish himself as an expert microscopist. Ultimately Darwin and others were to reject Ehrenberg's more salacious claims about the complexity of these microorganisms—but the boost to the technique of microscopy and the spur to reconsider the relationship between speculation and empiricism had lasting effects (Jardine 2009).

Ehrenberg's was just one of a host of new theories that seemed to indicate that the microscopic world was a universal explanatory resource. Fossilized infusoria made up many of the strata; cells were the organizing principle of life, and germs the carriers of disease. As the century drew on the microscope played an ever greater part in public health, especially following revelations about the role of polluted water in typhoid and cholera outbreaks in London (Figure 36.3).

With the microscope now established as an instrument of the classroom and teaching laboratory, it became the primary means by which heavily mediated "Nature" was brought under control in the new academic laboratories of the second half of the nineteenth century (Gooday 1991). Here the careful stage management of observations allowed laboratory science to attain the kind of authentic validity previously reserved for field investigation. Experimental rigor now served to separate the communities of microscopy, with reformers like T. H. Huxley claiming that the instrument could only be correctly used with expert training and in the context of the new professional science.

At the close of the nineteenth century Lister's and Goring's work of making microscope optics a matter of systematic inquiry was effectively completed by Ernst Abbe, who provided the theoretical limit of microscope optics and then worked with Carl Zeiss to produce apochromatic lenses that approached optical perfection. As microscopists began to understand the ways in which the nature of light and the human eye limited the potential power of microscopes, and as the cell theory gave a programmatic direction to research, methods of sample preparation became increasingly important.

Figure 36.3 "Monster Soup, commonly called Thames Water," an 1828 engraving by William Heath. Wellcome Library, London.

Techniques in staining specimens, for example—pioneered by Ehrenberg and brought to a wider audience in the work of Robert Koch—allowed ever greater resolution of the parts of the cell and the nature of bacteria. With the new techniques of microphotography, scientists could trade on the supposed objectivity of the camera. And the establishment of the microscope as the preeminent instrument of laboratory research meant that it entered into countless syllabi, and standardized student microscopes were made in their tens of thousands.

Modern Microscopy

It is beyond the scope of the present essay to deal even cursorily with twentieth-century microscopy. Indeed there are good reasons for denying that a history of the instrument in this period would make sense. The success in the nineteenth century of the new and self-contained discipline of microscopy swiftly led to its dissolution: the microscope became a tool of professionalization, which in turn sent the instrument into the separate domains of zoology, anatomy, entomology, and so on.

Perhaps the most promising approach to recent microscopy—and one which would maintain the interconnection between theorizing, trade and manufacture that I have pursued here—is the tracing of microscopes as they circulated between laboratories. For example Pedro Ruiz-Castell (2006) has shown, with a case study of a Soviet microscope in use in Franco's Spain, how the movement of instruments could overcome the most formidable of political obstacles. The movement of microscopes amongst colonial networks was of course a much more routine and long-established business. With the development in the nineteenth century of botanical and microbiological research on a global scale, and through the growth of research in tropical medicine in the early twentieth century, microscopy came to be deployed far from its earlier European locales.

Thinking of the most dramatic change in microscopy in the twentieth century—the invention in the 1930s of the electron microscope—it is clear that instrument studies has much to contribute to the history and philosophy of science more generally. Following the techniques and materials involved in electron microscopy, we can see that—although it was often cast as merely an extension of light microscopy—in fact the new instrument had much to do with X-ray crystallography, and was therefore bound up with the nascent discipline of biophysics. At the more mundane level, the persistence of light microscopy offers an excellent opportunity for analyzing "the shock of the old" in the laboratory setting (Edgerton 2007).

For some advocates of the study of the microscope, its story has offered an intriguingly materialist and technologically determinist alternative to mainstream historiography (Turner 1980). Yet this has had its pitfalls. For example, commonly made arguments about the "failure" of a field to develop owing to primitive optics are obviously and damagingly Whiggish. Here I have endeavored to show that continuities and important developments in the history of science need not solely be theoretical—they can be found in altered relations of trade and scholarship and in the techniques of showmanship, rhetoric, and illustration. The microscope is perhaps the most recognizable tool of science and yet, especially for its recent history, there is much still to understand about its use and significance.

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