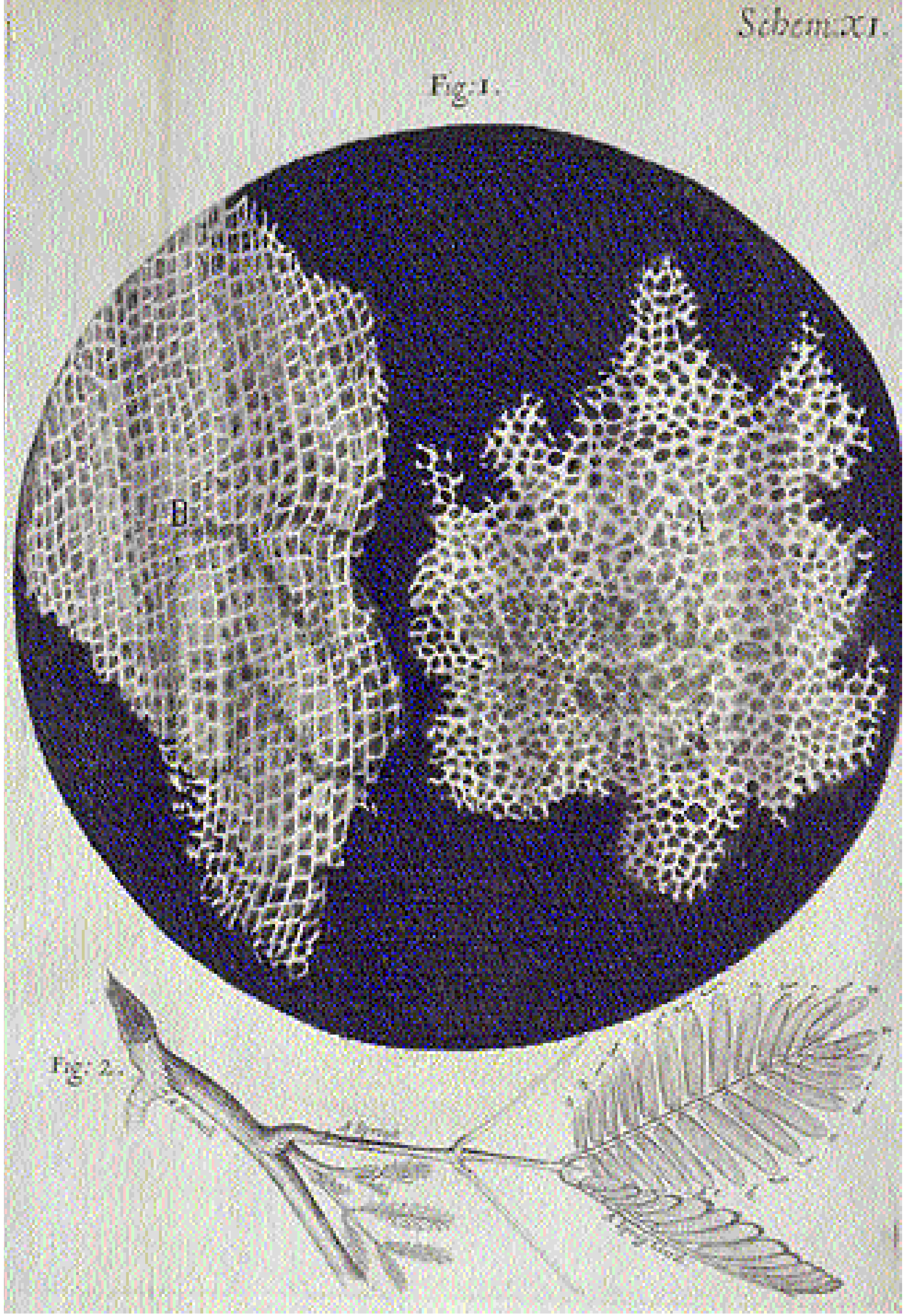


Robert Hooke

NATURAL HISTORY THROUGH THE MICROSCOPE

(1635–1703)

I have often thought, that probably there might be a way found out, to make an artificial glutinous composition, much resembling, if not full as good, nay better, then that Excrement, or whatever other substance it be out of which, the Silk-worm wire-draws his clew … This hint therefore, may, I hope, give some Ingenious inquisitive Person an occasion of making some trials, which if successful, I have my aim, and I suppose he will have no occasion to be displeas'd.'

This percipient prophecy of the invention of artificial fibres comes from one of the greatest books in early science. It was a large folio volume entitled *Micrographia*, published in 1665. The author, Robert Hooke, was the first professional scientist, being instructed on 25 March, 1662 by the Royal Society of London to present microscopical demonstrations at each of the Society's meetings. His book was full of wide-ranging speculations and descriptions of subjects ranging from lunar craters, needles and a razor to textile samples. Most of the pages were devoted to natural history through the microscope: Hooke produced breathtaking studies of ants, lice, fleas and gnats. The book became a best-seller and was reprinted two years later. *Micrographia* marked the dawn of popular science, and its repercussions have echoed on through the centuries. And it is still possible to buy a copy of this ground-breaking book, for facsimiles have been published over the years and are readily available.

Robert Hooke was born on 18 July, 1635 at Freshford on the Isle of Wight and was a sickly child, initially unable to attend school. Young Robert had a penchant for making scientific toys at home – including sundials and clocks – and learned Greek well enough to go to Westminster School. Even as a schoolboy he was said to have

Robert Hooke's best-known illustration shows a specimen of bottle-cork cut in longitudinal (left) and transverse section. Hooke noted that cork was made up of tiny rectangular boxes, like small rooms – hence his coinage of the term 'cell' that is with us to this day. He demonstrated this specimen at a meeting of the Royal Society of London on 13 April 1663, and later included it as Scheme XI of his great book, Micrographia *(1665).*

In March 2006 this 635-page, bound set of copies of Royal Society minutes, written out for his own reference by Hooke, came up for auction in London, but was secured in a last-minute agreement before the sale by the Royal Society for £1 million. The papers, posthumously indexed by Hooke's editor, William Derham, had remained in the Derham family for over three centuries.

invented 'thirty different ways of flying'. Later, at Oxford University, he came to the attention of the great Robert Boyle, who took him on as a research assistant. In 1660 Boyle helped found the Royal Society, and in November 1662 Hooke was appointed Curator of Experiments.

Microscopical Revelation

Contrary to popular belief, *Micrographia* was not the first book to be devoted to the microscope. That was Pierre Borel's *Observationum microscopicarum centuria* of 1656. Borel's was a small book of only 45 pages, however, whereas Robert Hooke's impressive volume was what we might now call a 'coffee-table book', with large pages and fold-out plates. Hooke's most famous microscopical observation is of cork, which on 13 April 1663 he showed to be made up of tiny square rooms or cells. This was how the term 'cell' entered biology – but Hooke was not observing living cells in cork, rather the dried walls of dead cells. Curiously, he had already seen living cells the week before, for on 8 April 1663 he had examined the tiny leaflets of a moss growing

on a wall. The published plate shows the cells clearly, and deserves to be recognized as a milestone in natural history.

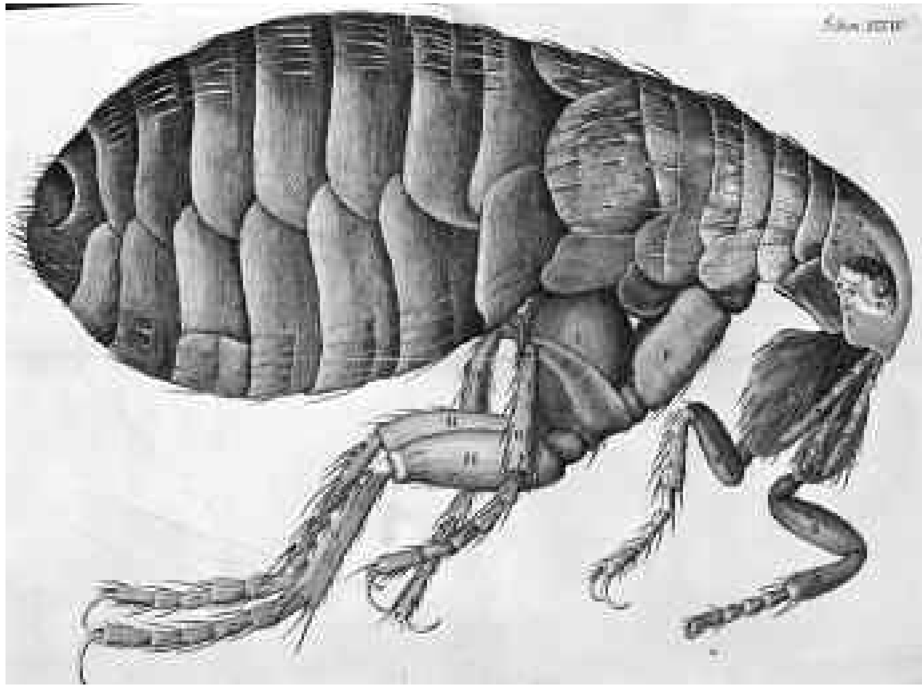
After the demonstrations of moss and cork, which he showed with samples of Kettering-stone, came a succession of other revelations: leeches in vinegar and mould on leather on 22 April; diamonds in a flint and a spider with six eyes on 29 April; male and female gnats (6 May); the point of a needle, the head of an ant and a fly (20 May). On 24 June, Hooke was told to work 'with Dr Wilkins and Dr Wren' to broaden his programme of demonstrations. John Wilkins was the Bishop of Chester and was Secretary of the Society, while Christopher Wren was a physician, although he is far more familiar now for his architecture, in particular St Paul's Cathedral in London.

Hooke's insights set in train much of the science that came later. For instance, his concept of the nature of light as a 'very short vibrative motion transverse to straight lines of propagation through a homogeneous medium' was the starting point for the work that was to make Isaac Newton famous. Hooke came to regard Newton as a plagiarist of his ideas, and would be incensed by the modern term for the rainbow-coloured fringes visible when two sheets of glass are pressed together – 'Newton's rings'. They were first studied by Hooke, and he really deserves to have his name attached to the phenomenon. His invention of the hygrometer and his study of capillaries ('small glass canes' he called them) were equally innovative.

Hooke's Legacy

Our knowledge of the breadth of Hooke's ideas has recently been extended by the rediscovery of a set of his hand-written notes from meetings of the Royal Society made between 1661 and 1682. These papers were due to be sold at auction in 2006, but at the last moment were bought for the Royal Society. Among the pages are descriptions of Hooke's design for an accurate timepiece, proposals for an experiment to demonstrate the earth's rotation, and accounts of his early work with the microscope. Hooke's interest in mechanics pervaded his life, and he applied his beliefs to the world of natural history too. Throughout *Micrographia* there is a mechanistic theme of the way in which physics could account for natural history.

Although the world of natural history dominates this impressive book, other fascinating and innovatory discussions lie within. It was Hooke who looked seriously at the fossilized remains of plants and animals, and recognized their true origins. Ammonite fossils, for example, were colloquially known at the time as 'serpent stones' and were believed to be snakes that has been cursed and turned to stone. Hooke discerned the truth. He wrote that, in his view, a deluge, earthquake or storm

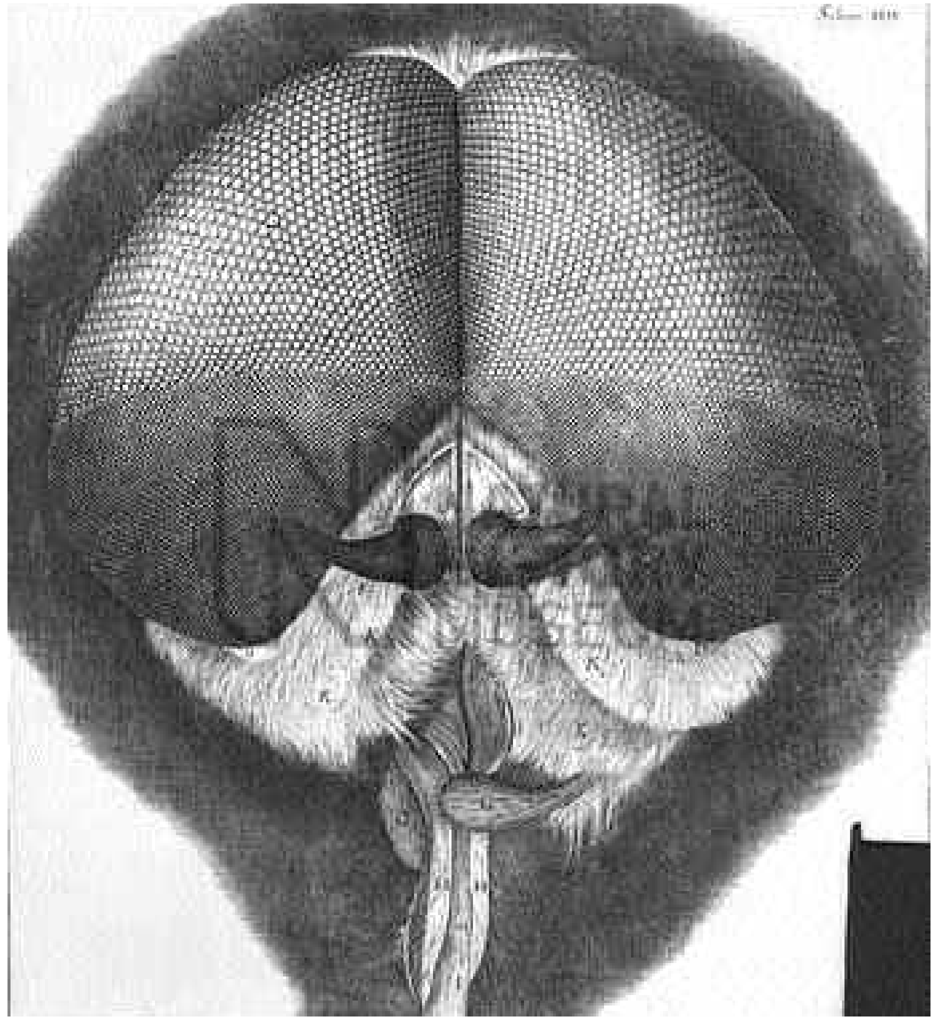


Hooke produced two spectacularly large folded plates for publication in Micrographia. *Almost as though in irony, these great plates showed two of the tiny parasites most familiar to his readers – a louse and a flea.* Pulex irritans*, the human flea, appeared as Scheme XXXIV, facing page 201.*

had thrown them together and that 'mudd, or clay, or petrifying water' had 'in tract of time … settled together and hardened in those shelly moulds' found in the modern world. It was a pioneering and surprisingly prescient insight into how fossils form.

Robert Hooke is remembered today for the law named after him, stating that a spring lengthens in proportion to the force applied, but he has also left a far greater, and more concrete, legacy – for example, he became Chief Surveyor of London after the Great Fire of 1666 and worked with Wren to rebuild the city. In later life his feud with Sir Isaac Newton grew increasingly bitter; as a result Newton did all he could to remove Hooke's name from the records. In the end, however, Newton's campaign came to nothing; Hooke is rightly recognized as a great pioneer and the first person to bring the microscopic sights of nature to an astonished public.

More remarkable is the fact that his book is still widely read in facsimile by modern students of the natural world. Tucked away in the unnumbered pages of the Preface is a description of how to make a single-lens high-power microscope. This was clearly consulted by the Dutch draper Antony van Leeuwenhoek (p. 104) during



The compound eye of insects had first been pictured by Francesco Stelluti in 1630. Hooke produced a striking impression of the head of a house-fly, with its spectacular compound eyes, for publication as Scheme XXIV, facing page 201 in his 1665 book Micrographia.

his visit to London in 1668. When Leeuwenhoek began his career as a microscopist of the natural world, it was Hooke's observations he replicated – and Hooke's design of microscope that he made.

It would please Hooke to know that his words are read by people today much more than those of Newton. And although we now have the discipline of non-Newtonian physics Hooke remains a constant. After a lifetime of tribulation and battling to establish his name, his reputation is assured.

Antony van Leeuwenhoek

THE DISCOVERER OF BACTERIA

(1622–1733)

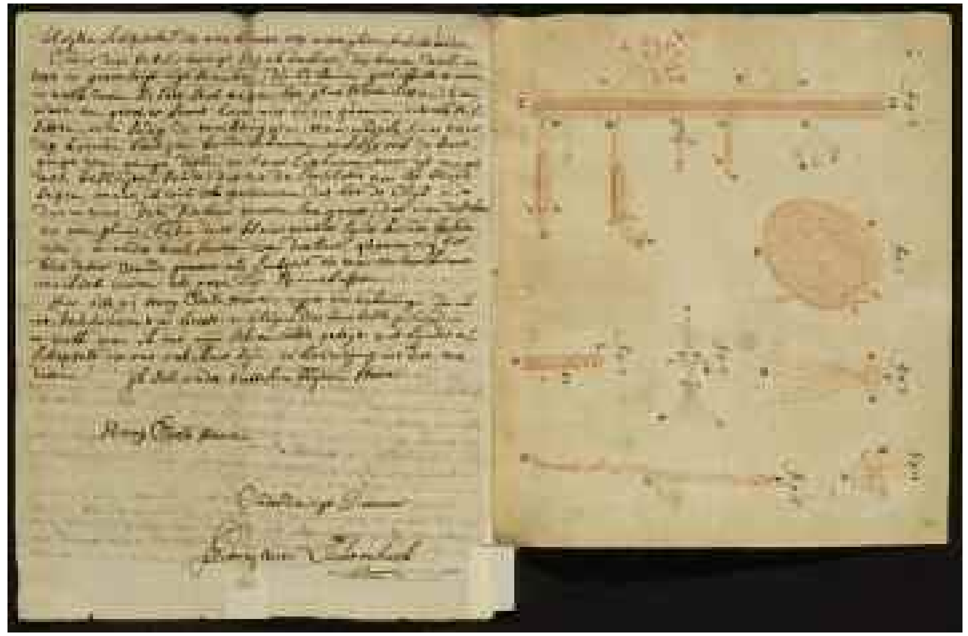
Looking at this water . . . the motion of most of these animalcules was so swift, and so various – upwards, downwards and round about, that 'twas wonderful to see. And I judge that some of these little creatures were more than a thousand times smaller than the smallest ones I have ever seen upon the rind of cheese.

source

With these words the modern science of microscopical biology was launched. They were written in Delft, the Netherlands, in September 1674, by an untutored draper and civic official; their author, Antony van Leeuwenhoek, is the father of microbiology. By discovering micro-organisms he took the greatest single step in biology of the entire 17th century, and one of the most fundamental in the whole history of natural science. His interest in the natural history of life beyond our normal vision was unique and proved to be crucial to the development of our understanding.

There are more microbes in a spoonful of soil than the total human population of the earth. Their variety is astonishing, and their importance is still little understood; more research than ever before is being done into the realm of these ordinarily invisible organisms. Yet until that momentous day when Leeuwenhoek put a glass phial of lake-water in front of his microscope lens, no one had any idea of the extent of the world's microbial populations.

Leeuwenhoek was born in Delft on 24 October 1632 and was christened on 4 November that year, his name appearing on the same page of the baptismal register as Jan Vermeer, who became Delft's greatest painter. Curiously, when the young Vermeer died, Leeuwenhoek (who was by that time a local civil servant) was appointed executor to Vermeer's estate, though there is no evidence that they ever met. After his father died and his mother remarried, Leeuwenhoek was sent away to school, aged six, and later went to live with an uncle. In due course he settled in Amsterdam to learn the drapery trade, but in 1654 he returned to live in Delft, where he was to stay for the rest of his long and distinguished life.



This pencil drawing by Leeuwenhoek's limner shows duckweed and microbes from a Delft canal. It was sent to the Royal Society of London with Leeuwenhoek's letter of 25 December 1702. The elongated structure in fig. 8 is the root of a duckweed plant seen under the microscope. Also clearly portrayed are rotifers, Hydra *and* Vorticella. *The drawing was engraved and published in Philosophical Transactions (vol. 23, p. 1291) and* Collected Letters 1939–1999 *(vol. XIV, pl. IX).*

In 1668, Leeuwenhoek visited London in the course of his work and while there he came across an extraordinary book filled with pictures of fleas and lice, bees and seeds, flies, midges and mould as seen through microscopes. The book, already in its second edition, was called *Micrographia*, and it was bursting with information about the amazing sights this new instrument could reveal; its author was the young Robert Hooke (p. 98). Both men were then in their thirties.

Micrographia was the talk of the town, and so it is no surprise that it came to the notice of a visitor from the Netherlands. Also, it contained fine engravings of fabrics seen through the microscope. Leeuwenhoek would have found these compelling, as drapers regularly used lenses to magnify cloth to assess its quality. After he returned home, Leeuwenhoek must have thought about Hooke's *Micrographia* and its astonishing revelations. Eventually, he began to develop a design for a simple microscope, exactly as set out by Robert Hooke in the Preface to his book, and soon others began to take notice. The physician, Reinier de Graaf, wrote a letter to the Royal Society in London in 1673, reporting that: 'a certain most ingenious person here named Leeuwenhoek has devised microscopes which far surpass those which we have hitherto seen.' That was in April. In August came another missive, this time from Constantijn Huygens, who wrote in support of: 'our honest citizen Leeuwenhook … a diligent searcher.'

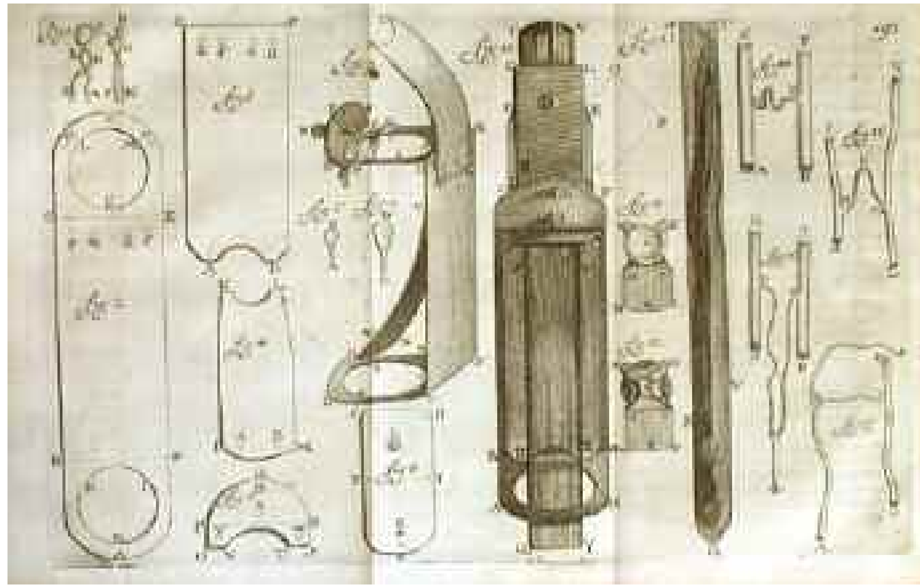
Leeuwenhoek's First Observations

Leeuwenhoek's first microscopical investigations were of mould, a bee and a louse – all of which were featured in Hooke's *Micrographia.* By June 1674 he was cutting superbly fine sections of biological materials and sending them to London, where I rediscovered them, still in excellent condition after 308 years, in the archives of the Royal Society – testimony to his extraordinary dexterity.

In each letter Leeuwenhoek wrote to the Royal Society he took issue with Hooke's descriptions in *Micrographia.* Hooke had made observations of the appearance under the microscope of cork, elder pith and the shaft of a feather, and in response were Leeuwenhoek's own descriptions of exactly the same choice of specimens, using Hooke's design for a high-power microscope.

And then came his momentous letter of 7 September, 1674. Leeuwenhoek described, in the homely and vernacular style he always used, how he had been crossing a lake named Berkelse Mere, and had paused to consider the lake water. In winter

The discovery by the author of original specimens prepared by Leeuwenhoek, and dating back three centuries, is one of the landmark revelations in the history of the microscope. A small portion of each was fixed to an aluminium stub, coated with gold to render it electrically conducting, and examined by the author at Cardiff University under an electron microscope, with the agreement of the then President of the Royal Society, Sir Andrew Huxley (himself a noted microscopist).



When Peter the Great of Russia came to Delft to learn more about boat-building, he arranged to meet Leeuwenhoek, who gave him one of his microscopes. This diagram (published as plate 193 in the Arcana Naturae detecta ab Antonio van Leeuwenhoek*, 1695) shows the kind of instrument that the Dutch microscopist gave the Czar, who took it back to St Petersburg with him.*

it was clear, he wrote, but as the summer drew on small white or green growths began to appear. The locals told Leeuwenhoek that they were caused by the evening dew, but he was not convinced. 'I took up a little water in a glass phial', he wrote, 'and examining it next day I found floating therein diverse earthy particles ….'

Some he said, were like a human hair, but with green spirals inside. There is no mistaking his description: this was the chlorophyte alga *Spirogyra.* This species contains its chlorophyll – vital for photosynthesis – inside spiral strips that run the length of the cells, looking like a green spring. These are the 'green spirals' about which he wrote. Some were round, he said, and others were oval; he saw some with 'two small legs near the head, and two small fins at the hindmost end of the body.' These were surely the wheel-animalcules we now call rotifers. They are tiny creatures, just visible to the naked eye, that move about propelled by circles of beating hair-like cilia. They look much like wheels, or projecting horns.

'Others,' he wrote, 'were green in the middle and white in front and behind'. You might find that description familiar … it is the green alga which was always popular in school books on biology, *Euglena viridis.*

During the following year, Leeuwenhoek began systematically examining samples of freshwater, and soon reported seeing small creatures with minute limbs moving ceaselessly about. They were clearly not water fleas: 'those little animals appeared to me ten thousand times smaller than those represented by M. Swammerdam and by him called water-fleas ….' These, Leeuwenhoek wrote, could be perceived by the naked eye. His organisms were too small by far for that.

He sent a full account to Henry Oldenburg, secretary of the Royal Society, on 9 October 1676, and extracts were presented at the fortnightly Society meetings throughout February 1677. A section of the letter was printed in *Philosophical Transactions* dated March 1677. Another summary of Leeuwenhoek's startling discoveries was sent to France and appeared in *Journal des Sçavans* in 1678. His observations were by now being widely discussed by natural philosophers – Leeuwenhoek was observing microscopic life as nobody before had ever done, and his discoveries were set to revolutionize natural history.

The Making of the Microscopes

How could someone make a microscope at home sufficiently powerful to observe bacteria, fungi and minute algal and protozoan cells – as Leeuwenhoek did? The secret lies in the simplicity of the design. Generally, the microscopes of the mid-17th century (like those of the modern era) were tall, grand designs with separate lenses to approach the specimen and to focus the image. Lenses generate aberrations in which spurious colour, and irregular fields of focus, distort the reality of what is observed. When lenses are fitted together, they magnify the aberrations.

Portrait of Leeuwenhoek in oils by Jan Verkolje, 1686. He is shown holding one of his famous microscopes.

There is a simple way to overcome this problem – use one lens instead of several. A single tiny lens, about the size of a pin-head, can create images that are magnified hundreds of times and yet show remarkably little distortion. Leeuwenhoek used to grind a single tiny lens and fixed it in between two metal plates with apertures – the lens fitted securely between them. A system of screws attached to the plates allowed the user to move and focus the specimen. It was an ineffably simple solution to the problem, and allowed Leeuwenhoek to turn out hundreds of microscopes without any complex instrument-making. Two questions immediately arise. First, why did Leeuwenhoek not use a compound microscope like the other

microscopists of his day? Secondly, since Leeuwenhoek's design was clearly based on that described by Hooke in his preface to *Micrographia*, why did Hooke not use a simple microscope, especially if the results were so impressive? Using single lenses Leeuwenhoek made microscopes that could magnify up to 300 times; most of the drawings in Hooke's book were enlarged only one-tenth as much.

Utrecht University Museum holds this brass microscope, no bigger than a postage stamp, made by Leeuwenhoek. Unusually the lens is blown rather than being ground.

Hooke preferred a compound microscope because it was impressive, beautifully tooled and professionally produced. In addition, his was purchased for his work at the Royal Society. Leeuwenhoek knew no instrument manufacturers and could not have afforded a microscope even if he had. He was an amateur with scarce resources yet with a burning enthusiasm to make microscopes. As for Hooke and the simple microscopes, the truth is that he did use them. His studies of lice and fleas were certainly made with a compound microscope, but this kind of instrument cannot resolve the fine details that Hooke includes in his magnificent engravings, which must have observed through a simple microscope. Clearly, Hooke used his compound microscope for general views, but filled in the fine details with a simple one.

It was Leeuwenhoek's determination, stubbornness and single-minded enthusiasm that drove him to use a simple microscope for the fifty years of his career in microbiology. Hooke had given up after just a few years, mainly because hand-held simple microscopes were difficult to use. Such practical difficulty was no obstacle to Leeuwenhoek.

Describing Microscopical Nature

Leeuwenhoek's descriptions are vivid and natural. In the middle of September, 1675, he sat with his microscope in hand and with a tiny glass tube held in position with a small blob of wax. He wrote with a quill pen, stopping and starting as his observations progressed, eagerly watching everything that went on inside this diminutive microbial universe.

'They sometimes stuck out two little horns, which were continually moved in the manner of a horse's ears. The part between these little horns was flat, their body otherwise being rounded, save only that it ran to a point at the rear end; at which pointed end it had a tail, nearly four times as long as the whole body, and looking as thick, when viewed with my microscope, as a spider's web. At the end of this tail there was a pellet, of the same size as one of the globules within the body, and I could not perceive this tail to be used by them in the open water. … I have seen several hundred little creatures, caught fast by one another in a few filaments, lying within the compass of a grain of coarse sand.'

It would be difficult to misunderstand such clear descriptions, or to fail to be enraptured by the sheer sense of excitement and determined enthusiasm that drove his meticulous investigations of the microscopical communities that met his astonished eyes. Leeuwenhoek was breaking new ground, and knew it; by 1686 he felt he was of sufficient distinction to acquire a 'van' in his name, and was known as Antony van Leeuwenhoek thereafter. Royalty were aware of him, statesmen came to visit him; he was elected to the Royal Society.

Breadth of Endeavour

During his incomparably productive life Leeuwenhoek turned his microscope on virtually everything he could find. However, it was his extensive studies of living micro-organisms that underpin his reputation. His descriptions are clear, and properly balanced by a capacity for self-criticism and objectivity. He has always had his detractors, however. A generation ago, students were being taught that Leeuwenhoek could not possibly have observed what he claimed, and he has frequently been regarded as a dilettante who imagined much of what he wrote. So is it possible to see the diminutive organisms that Leeuwenhoek claimed to observe? Using modern replica microscopes with a single lens and also with the Leeuwenhoek microscopes that still survive, including the original microscope preserved at the Museum of the History of Science at Utrecht University, experiments by the author have shown that single lens microscopes can indeed resolve the algae and protozoa Leeuwenhoek described, and can even reveal living bacteria. A study of blood revealed the erythrocytes (red cells) with clarity, and even the lobed nucleus within a leucocyte (white cell).

Although he did not begin his career in microscopy until he was already 40, Leeuwenhoek went on to give half a century to unremitting research and made a host of crucial revelations. When he lay dying, aged 90, he was still engaged in microscopy, examining gold-bearing sands for clients in the East India Company. The respiratory condition he suffered at the end of his life was so well described that it still bears the name of Leeuwenhoek's Syndrome. Nobody could have imagined that so much insight would be triggered by a chance observation of cloudy lake-water … not even Antony van Leeuwenhoek himself.