



## CRITICAL FOCUS

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### Breaking the Myths of Microscopy

Everybody knows the light microscope as the symbol of science — the universal touchstone that people immediately associate with high-end scientific research. But there is another side to this coin that is rarely discussed: Most of what we're told about its origins is wrong. When people look back at the development of the microscope, they downgrade its practitioners and their skills in a uniquely patronizing fashion. It doesn't happen anywhere else in science. The work of the early astronomers is described with awe, pioneering surgeons are admired for their courage and dexterity, groundbreaking engineers are regarded as brave pioneers, and every physicist is a genius. But not the early microscopists. They are portrayed as inquisitive amateurs, who simply slashed into a few plants and got lucky.

People find it hard to accept that the earliest investigators were capable of achieving what they claimed. The standard accounts agree that the microscope pioneers could observe nothing more than blurred images of specimens that they roughly ripped apart. They were not farsighted innovators but diletantes and hobbyists. Guesswork was their guide, and good fortune underpinned their discoveries. By the time science had introduced color-corrected achromatic microscopes, people agree that sensible discoveries began to emerge. But we are endlessly told that the

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*The first microscopists are often viewed as amateurs who got lucky with their handmade microscopes, but it was they who developed the techniques used today.*

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early microscopes were crude, their users uneducated and their techniques primitive. Truly, there is no comparable area of discovery where the pioneers have been systematically denigrated and the results of their research so widely misconstrued.

Here is the surprising truth. In the first two centuries, before the modern achromatic microscope was born, all the groundwork had been laid. That vast unseen cosmos of microscopic algae, protozoa and fungi, the cell and its nucleus, crystals and feathers, hairs and pollen grains, had been documented and described. The techniques on which we now rely had been launched, so here is remarkable revelation that flies in the face of the accepted view: Techniques from before the era of those sophisticated achromatic microscopes are with us in our present-day laboratories. You could do much of today's routine microscopy with a handmade microscope from the 1600s, and a cheap, simple microscope could usefully be used in today's fieldwork.

The microscope pioneers became the focus of my plenary presentation to the Microscopy Society of America in Hartford, CT in August 2014. For the first time, I was able to show more than 1,200 microscopists exactly what could be seen through microscopes from the dawn of science. Video images in real time revealed the specimens as they were first observed by natural philosophers, including Robert Hooke from

England, Antony van Leeuwenhoek from the Netherlands and Robert Brown from Scotland. As the video reconstructions unwound, the eyes of the audience grew wider by the second. Delegates were transfixed by the sheer beauty of the images and the unexpected detail that simple microscopes could disclose to the keen eye of the observer. Suddenly, we were carried back to the birth of the microscope and the dawn of modern science. The presentation was greeted with unusually prolonged applause — not for the speech, but more for the astonishing revelations of what was achieved in the 17th century.

These new findings revolutionize the way we look back at the history of the microscope, and it can no longer be acceptable to patronize those pioneers. This tendency to belittle the first microscopists is pervasive. Here is an example from a narrow-minded commentator, who was seduced by the idea that a Leeuwenhoek microscope was incapable of high resolution. In order to observe bacteria, this account states that Leeuwenhoek “must” have employed darkfield microscopy, in which the organisms shine out against a black background. Says the report: “In normal microscopy the bacteria are simply invisible.” That comment is wrong. We have now shown precisely how Leeuwenhoek observed bacteria using normal lightfield microscopy.

The account goes on to assure the reader: “Leeuwenhoek used another lens — held by hand in front of the microscope plate — to give a secondary magnification of the image.” Wrong again. There is no evidence that Leeuwenhoek needed to supplement his lenses, and we can now demonstrate that secondary magnification was unnecessary. Leeuwenhoek’s diminutive, beautifully hand-crafted lenses could resolve microbes without such assistance.

There are several noteworthy facts concerning those remarks. First, they are not old Victorian pronouncements, born of ignorance; they date back no more than 40 years. Secondly, the author’s unfamiliarity with the subject is hard to explain since he had already published on the origins of the microscope and should have been less convinced of Leeuwenhoek’s reliance on subterfuge in teasing results from unsophisticated instrumentation. Thirdly, I am personally aware of the shortcomings of those descriptions for a very obvious reason — the author of those words was me.

## BROWN’S DISCOVERY?

Of all the eponymous microscopical discoveries, the most widely known is “Brownian motion.” It was

named after the Scottish microscopist Robert Brown (1773–1858), who began his adult life as a medical surgeon and ended up as a botanist. Brownian motion refers to the ceaseless movement of minute particles as they are seen to be ceaselessly bombarded by molecular movement when observed under a high-power microscope. The descriptions of Brown making his observations are almost all incorrect. The How Stuff Works website ([www.howstuffworks.com](http://www.howstuffworks.com)) says: “Brown had noted and studied the agitated motion of very fine pollen grains suspended in water.” The NRICH Enriching Mathematics website ([nrich.maths.org](http://nrich.maths.org)) says that Brown saw how pollen grains “jiggled about”; and the Einstein Year website ([www.einsteinyear.org](http://www.einsteinyear.org)) says, “Robert Brown noticed that if you looked at pollen grains in water through a microscope, the pollen jiggles about.” Bill Bryson’s popular writings say the same. They are all wrong.

Turn on the television and you will find a BBC series called “The Atom,” in which the presenter Jim Al Khalili sets out to demonstrate Brownian motion. He smiles knowingly at the camera and then sprinkles some pollen dust onto a tub of water. “A Scottish botanist named Robert Brown sprinkled pollen grains in some water and examined it through a microscope,” he explains. “Instead of the pollen grains floating gently in the water, they danced around furiously,” adds Khalili, describing this as “Brown’s discovery.” But it wasn’t, and Brown never claimed it was. And in spite of the commentary, the pollen grains never moved. The account is false.

The phenomenon we know as Brownian motion had first been recorded in 1785 by Jan Ingenhousz, who observed the motion of charcoal dust (*Nature*, 641, June 7, 2001). That is more than 40 years before Brown. Particles of carbon are a popular way of observing Brownian motion, and when the producers of “The Atom” assured the audience that they were showing us pollen grains, they actually screened carbon particles in Indian ink filmed under a high-powered modern microscope and not “pollen grains” at all. The commentary wasn’t honest. There is a sequence of jiggling pollen later in the program, but it is also a fake. The producers created some computer-generated imagery (CGI) objects (bearing little resemblance to pollen), which were programmed to wobble from side to side. You might propose that, in this modern era, a CGI version is a convenient means of demonstrating the phenomenon, but no, it truly is a fake. The truth is that pollen grains do not jiggle about under a microscope. They never did.

The particles that Brown observed to be in cease-

less motion were actually observed *within* the pollen grains. He is precise on this point. Brown's observations remind us of his dexterity as a microscopist. Mounting pollen grains so that their contents can be observed requires a smooth glass slide and a coverslip (very likely cut by Brown from slivers of mica). It also necessitates meticulous focusing and diligent manipulation to select the relevant details. All this Brown undertook without the benefits of any instruction. His observations were never of pollen grains in motion, for his beautifully written account clearly shows that they remained obdurately motionless. Reference books and websites copy from each other rather than from original sources, and so the myth of the jiggling pollen has spread worldwide.

In 1991, Daniel H. Deutsch of Pasadena, CA added his name to the list of detractors by concluding that it was theoretically impossible for Brown to have witnessed Brownian motion. The news reached me just as I was about to prepare my presentation for the Inter/Micro conference in Chicago in 1992, so I put together my findings and showed to the audience exactly how Robert Brown made his observations. There is a good commentary on the controversy online (search for "Brownian motion freelibrary") and a summary of the research was published in my paper for *Nature* (359, p 265, Sept. 24, 1992). It triggered worldwide interest, and I then detailed Brown's remarkable achievements in *The Microscope* (40:4 pp 235–241, 1992).

I regularly asked the authorities to change their published descriptions, but this was not an easy task. At the time I was science advisor to *Encyclopaedia Britannica* which, had been published in Chicago since the 1930s. They hesitated to change the description, and their account in the 15th edition, published in 1995, still stated: "Brown noticed a "rapid oscillatory motion" of the pollen grains suspended in water." The editors were unwilling to publish a correction because the error was mirrored in every standard reference book, and they hated to be the odd one out. Once a detail has been dignified in print, it becomes a major task to change it. It was years before the battle was won, though in the present online edition the phenomenon is at last properly described.

## METICULOUS MICROSCOPY

Brown's other great discovery was the ubiquity of the cell nucleus, and once more this reminds us how meticulous he was as at microscopical technique. Others had observed the nucleus before, and some had drawn it. The nucleus had first been observed and re-

# THE PHILOSOPHICAL MAGAZINE AND ANNALS OF PHILOSOPHY.

[NEW SERIES.]

SEPTEMBER 1828.

XXVII. *A brief Account of Microscopical Observations made in the Months of June, July, and August, 1827, on the Particles contained in the Pollen of Plants; and on the general Existence of active Molecules in Organic and Inorganic Bodies.* By ROBERT BROWN, F.R.S., Hon. M.R.S.E. & R.I. Acad., V.P.L.S., Corresponding Member of the Royal Institutes of France and of the Netherlands, &c. &c.

[We have been favoured by the Author with permission to insert the following paper, which has just been printed for private distribution.—Ed.]

THE observations, of which it is my object to give a summary in the following pages, have all been made with a simple microscope, and indeed with one and the same lens, the focal length of which is about  $\frac{1}{2}$ nd of an inch\*.

The examination of the unimpregnated vegetable Ovulum, an account of which was published early in 1826†, led me to attend more minutely than I had before done to the structure of the Pollen, and to inquire into its mode of action on the Pistillum in Phænogamous plants.

In the Essay referred-to, it was shown that the apex of the

\* This double convex Lens, which has been several years in my possession, I obtained from Mr. Bancks, optician, in the Strand. After I had made considerable progress in the inquiry, I explained the nature of my subject to Mr. Dollond, who obligingly made for me a simple pocket microscope, having very delicate adjustment, and furnished with excellent lenses, two of which are of much higher power than that above mentioned. To these I have often had recourse, and with great advantage, in investigating several minute points. But to give greater consistency to my statements, and to bring the subject as much as possible within the reach of general observation, I continued to employ throughout the whole of the inquiry the same lens with which it was commenced.

† In the Botanical Appendix to Captain King's Voyages to Australia, vol. ii. p. 534. *et seq.*

New Series. Vol. 4. No. 21. Sept. 1828.

Robert Brown first described the ceaseless motion of tiny particles, which we now call Brownian motion, in this paper dating from 1828. The meticulous typesetting alone shows the care that was taken in scientific publishing, yet these pioneering discoveries are frequently downplayed by present-day commentators.

corded by Leeuwenhoek in 1719, where he observed nuclei in the blood cells of salmon. It was then described by Franz Bauer in 1804, and Brown made his observations of the leaf cells of orchids in 1827. It was because of Brown that the nucleus acquired its name. He wrote: "In each cell of the epidermis of a great part of this family, especially of those with membranous leaves, a single circular areola, generally somewhat more opaque than the membrane of the cell, is observable. This areola, which is more or less distinctly granu-



Robert Brown used this fine microscope in his pioneering research. Made by Bancks of London, this instrument packs away into a mahogany box that forms the base of the microscope during use. Despite its diminutive size, it provides images of surprisingly good resolution. The Linnaean Society holds this microscope, which the author restored to working condition in 1981.



Among Brown's discoveries was the continual streaming of cytoplasm within living cells. He observed these staminal hairs of *Tradescantia virginiana* with his diminutive microscope, which produced this image. Note that the nucleus (center, top) can be clearly discerned within the cell, which belies the skepticism that has more recently been shown.

lar, is slightly convex. ... This areola, or nucleus of the cell as perhaps it might be termed, is not confined to the epidermis, being also found ... in the parenchyma or internal cells of the tissue." The account was published in his paper, "On the Organs and Mode of Fecundation of Orchidea and Asclepiadea," which was originally published in 1833 and appeared in *Miscellaneous Botanical Works* (Vol. 1, pp 487–543, London, 1866).

When the BBC came to tell the story in a television program called "Cell," they failed to capture Brown's remarkable vision of the nucleus. Their world-class filmmakers could not strike a focused image through Brown's little microscope, which they dismissed as if it were not much more than a toy. The program presenter, Adam Rutherford, was almost mocking in his tone. He described how botanists had been "eagerly tearing up plants to study their anatomy." What was that? "Tearing"? This is a classic example of the way modern commentators like to belittle the work of the pioneers in microscopy. Of course they didn't "tear" tissues — they dissected their specimens with astonishing diligence.

Brown had used his infinite patience and steady hand to trace the fertilization processes of plants, and it was Brown who recognized that the ovule in the cone-bearing gymnosperms is naked (in the more highly evolved flowering plants, the angiosperms, the ovule is wrapped in layers of protective tissues). This is an exceedingly difficult observation for a modern microscopist to make, and in Brown's time it was an extraordinary achievement. Once again we can see the extent of his dexterity and microscopical technique, which modern microscopists would be hard-pressed to emulate.

The microscopes that Brown used were made for him by the father-and-son firm of instrument makers Bancks of London. Their microscopes were diminutive instruments that remain a joy to use. It was these he used to observe the fine details of plant anatomy, including his recognition of the cell nucleus. With the benefit of his experience in microscopy, Brown later turned to Dollond and asked him to make similar microscopes of advanced design. Meanwhile, Brown was developing a sophisticated microtechnique; the idea that he was "tearing" the tissues apart is ridiculous. Brown was laying the foundation for techniques we use today.

Many writers have been similarly dismissive of the dexterity of the pioneers. In his *History of Microtechnique*, published in 1973, Brian Bracegirdle wrote: "The first microscopists paid less attention to their specimens, for anything visible was impressive by its sheer

novelty." He added: "The detail visible in the usual dry mounts is minimal, and they are prepared with little finesse, so that although they held sway until as late as the 1830s, they have so little resemblance to life that scientific interpretation is almost impossible."

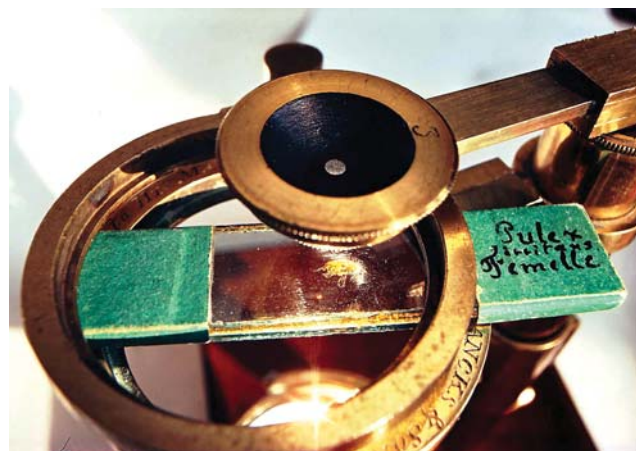
Brown had shown that, far from using dry mounts prepared with "little finesse," he was observing freshly dissected tissues, and his preparative techniques involved a high degree of precision. I have even found evidence of the way plant specimens were prepared, for one of the surviving Bancks microscopes bears the evidence to this day. It was made in the 1820s for George Bentham. Like so many of the early investigators, Bentham showed remarkable abilities. By the age of seven he could speak German, French and Russian, and when he went to stay in Sweden some time later he acquired that language, too. Bentham became acknowledged as the premier systematic botanist of his generation; he traveled widely, eventually visiting every herbarium in Europe.

I can discern the traces of the way he worked from marks that remain visible on his Bancks microscope. Bentham examined floral microanatomy by probing deep into his specimens and examining them repeatedly under the microscope as the procedure progressed. If we look closely at the brass block at the top of his microscope, the tiny cuts from his blade can still be discerned. These cut marks exemplify the hardness of the steel and the sharp edge of his dissecting instruments, and they show us that he was observing the process in real time. He was clearly not content to prepare specimens in a leisurely fashion at his desk but was reviewing his material on the microscope stage and observing as he worked. Like Brown, George Bentham used technically exacting procedures.

## INSTRUMENTS OF WONDER

The use of these simple microscopes was widespread in the mid-Victorian era, though their capacity for high-quality microscopy was forgotten in later decades. During the latter half of the 20th century the achromatic microscope came to prominence, and the design of instrument used by the pioneers was by this time used only for low magnifications. As a consequence, microscopes like those of Bancks were dismissed as "simple dissecting microscopes."

Robert Brown was for many years a prominent figure at the Linnean Society of London, holding the positions of clerk, librarian and housekeeper (1805–1822) and eventually president (1849–1853). His microscope, which I restored in 1981, is now on display

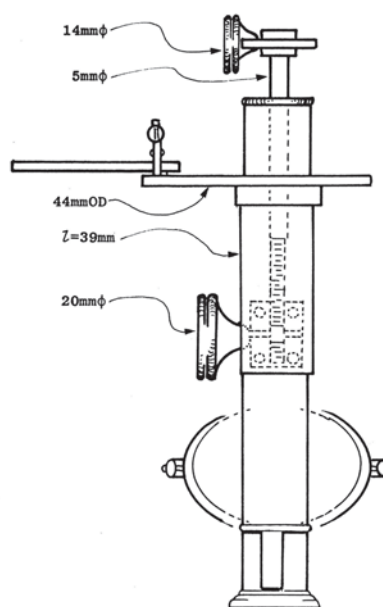
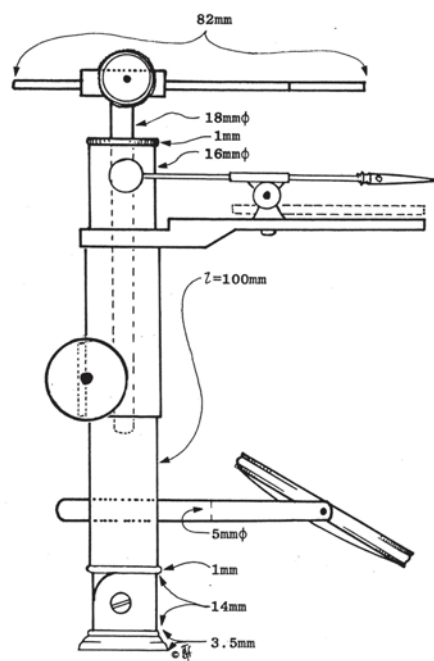


Bancks, the name of the manufacturer, can be seen engraved on the stage of this delicate little microscope once owned by botanist George Bentham. The brass block (top right) shows minute cut marks left by Bentham's carbon steel razor. This shows us that he dissected his specimens during sequential observations.

in the entrance foyer of the Linnean Society and had been lost for decades after his death, until a package was delivered to the Society. It was dated Jan. 19, 1932, and the accompanying letter said: "I have much pleasure in offering Mr. Brown's microscope to the Linnean Society if they care to accept it. Its credentials are in the box with it ... its history since the original owner is accounted for. Yours faithfully, (Miss) Ida M. Silver."

At that time, the Linnean Society was planning to commemorate Brown's first publications on the cell nucleus, and you would expect that the sudden discovery of the original microscope would have been greeted with excitement. You'd be wrong: the experts decided that it was too crude an instrument to have resolved anything as diminutive as the cell nucleus. The Linnean Society's annual report dismissed it as "surprisingly simple, being little more than a dissecting-microscope." Instead of being celebrated, it was locked away in a cupboard. There it stayed until 1951, when the organizers of the great Festival of Britain exhibition asked the Linnean Society if they could exhibit Brown's microscope. The Society declined. This primitive instrument simply wasn't worth the effort.

In 1982, I was appointed Honorary Surveyor of Scientific Instruments at the Linnean Society and was asked to report on Brown's microscope. I found it discolored and dusty, with the focusing controls seized solid and the lenses dirty. With care it could be restored to life, and once more we could see the traces left by Robert Brown. Around the body pillar we could



Measured drawings of Robert Brown's microscope held by the Linnaean Society show the essential design. Coarse focusing was carried out using the knurled control. Fine adjustment was made by easing pressure on the lens mount (top), which was held by a cylinder of cork cut to fit within the body pillar.

once again see the marks worn by his forefinger rubbing the brass as he focused up and down. It brought the era of Robert Brown closer to the present day and reminded us that this was not simply an old microscope, but the well-used agent of investigation by a brilliant microscopist.

These days the name of Banks as a microscope maker is unfamiliar. In addition to Brown and Bentham, many prominent people of their era owned a Banks microscope, including Sir William Hooker, director of the world-famous Kew Gardens and Charles Darwin, who took his instrument on the voyage of the *Beagle*. (Darwin's career as a microscopist is discussed in *The Microscope*, 59:3, pp 129–137, 2011.) Another Banks owner was King George IV, who is said to have suffered from porphyria; he became the central figure of the 1994 movie "The Madness of King George."

These "simple dissecting microscopes" were actually instruments of wonder, and the insights from research they facilitated are all around us today. How can we assess the procedures that these pioneers developed and the quality of their work? Many commentators have said that the first microscopists like Leeuwenhoek were guided largely by guesswork, though the truth is very different. Many of our modern microscopical techniques stem from the endeavors of these ingenious pioneers. Reinier de Graaf, the anatomist who first put Leeuwenhoek in touch with the Royal Society of London, wrote of experiments in which he injected colored fluids to study the course of

blood vessels in 1686, the same year in which Anton Nuck pioneered the injection of mercury to delineate blood vessels. In his book *Thesaurus Anatomicus Septimus* (1726), Frederick Ruysch describes how he developed the idea further by studying the pathways of the lacteal ducts and lymphatic system. He inflated them with air injected through fine straws and perfected the injection of wax into blood vessels. Eventually, he was able to preserve entire organs through this technique. In modern times, the public exhibitions of human cadavers injected and preserved by plastination have attracted worldwide interest. The idea is said to have been invented by Gunther von Hagens in 1977, but the principle had originally been pioneered by Frederick Ruysch — himself inspired by Nuck and Jan Swammerdam — in the Netherlands more than 250 years earlier.

## LEEUVENHOEK'S EXPERTISE

Although we could appreciate the writings of the early microscopists and recapture a flavor of their work from their descriptions, investigations were hampered by a lack of actual examples. Bracegirdle summed it up in 1973: "No preparations from the seventeenth century have survived, for it is almost certain that they were only of a temporary kind, for viewing on one occasion only." That was the prevailing view — and it proved to be wrong.

In February 1981, Sir Andrew Huxley, then presi-



Four Bancks microscopes are reunited after two centuries: (from left to right) an advanced microscope owned by Robert Brown, Sir William Hooker's microscope and the instrument owned by George Bentham, which are all preserved at Kew Gardens, London. Brown's Linnean Society microscope (far right) completes the quartet.

dent of the Royal Society of London, invited me to scrutinize the original letters sent by Leeuwenhoek to London. Jokingly, I said that we might find contemporaneous pollen grains, or hairs from Hooke's wig among the letters. Little did either of us imagine that I would discover nine of Leeuwenhoek's original specimen packets, sent to London between 1674 and 1686, and that they would reveal just how masterful was the microtechnique developed by Leeuwenhoek as the world's first microbiologist (see *The Microscope*, 59:1, pp 11–19, 2011).

You will know Antony van Leeuwenhoek (1632–1723) as the celebrated Dutch draper, who studied microscopy as a vocation and devoted himself to exploring the microbial universe. Widely dismissed as a dilettante and hobbyist, he was actually an innovator of extraordinary perspicacity and prescience, who introduced several of the laboratory techniques that underpin today's microscopical research.

The first packet of Leeuwenhoek's specimens that I came across dated from June 1674, and I found that they contained sections of elder pith and cork. Many books have commented on Leeuwenhoek's observations, and sometimes they include photographs made by present-day microscopists to show how Leeuwenhoek prepared his sections. Rarely do they

do justice to the man. The methods used to prepare many modern sections are crude when compared with Leeuwenhoek's formidable expertise. By studying fine sections of cork, Leeuwenhoek was reprising observations made by the English microscopist Robert Hooke, the Royal Society's renowned demonstrator and the first professional scientist in the world.

On April 13, 1665, Hooke had prepared thin cork sections for examination and showed that they were comprised of tiny rectangular boxes that he named cells — the term we use today. Ingeniously, Hooke related this microscopical structure to the known properties of cork (its lightness and compressibility, etc.). This description caught Leeuwenhoek's attention, and he set out to replicate Hooke's discovery. Using a carbon-steel shaving razor that was sharpened to perfection, Leeuwenhoek cut sections of cork of great fineness and delicacy. I found these samples hidden among his surviving letters.

My studies revealed that Leeuwenhoek had used Hooke's ingenious method of ensuring that his sections remained intact. He sectioned the cork using a slightly upwards sloping cut, so that the specimen became progressively thinner. Just as it was so fine that it began to break apart, he diverted the direction of cut slightly deeper, thus giving the section additional

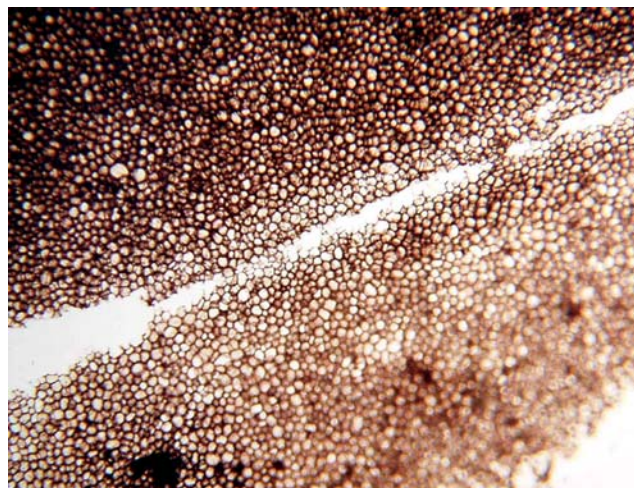


Typical of the silver microscopes made by Antony von Leeuwenhoek, this example was purchased in 2009 for nearly half a million dollars by an anonymous bioscience company at Christie's auction house in London (reported by Gary J. Laughlin in *The Microscope*, 57:1, ii, 2009). This photograph was kindly provided by James Hyslop of Christie's.

strength. The thinnest regions are wonderful to examine under the microscope, and are finer than many present-day sections.

Leeuwenhoek saw himself as a rival to Hooke, though my researches showed that Hooke was the source and the original inspiration for Leeuwenhoek's lifetime of devotion to microscopy. Leeuwenhoek wouldn't refer to Hooke by name, alluding to "a certain gentleman" instead.

For centuries people speculated on why Leeuwenhoek had become interested in microscopes. The matter was resolved in 1981, when I noticed a crucial paragraph in Hooke's writings. Hooke had published his microscopical work (along with speculations



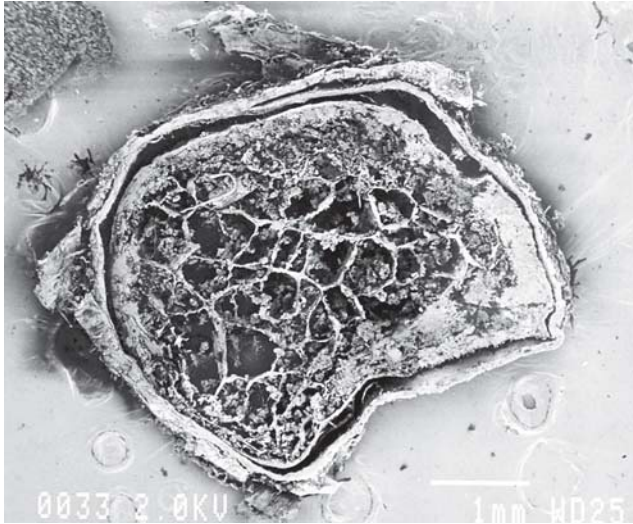
Fine sections of cork were found in a small paper envelope fixed to Leeuwenhoek's letter dated June 1, 1674. The technique he had used alternated thicker regions (for strength) with finer sectioning (for detailed observation). Robert Hooke had first published descriptions of cork sections cut in this way in his book *Micrographia* published in 1665.

about light, astronomy and the origin of the moon) in a beautiful book titled *Micrographia*, which appeared in 1665. Leeuwenhoek was in London the following year when Hooke's great book was the talk of the town. In the preface, Hooke explains how to grind lenses and mount them in perforated metal plates, which was precisely the design of instrument that Leeuwenhoek went on to manufacture. Hooke was the Dutchman's inspiration, and it was to replicate Hooke's studies of cork that led Leeuwenhoek to cut his own sections — the specimens that I found in London, still in their original envelope.

## SKILLFUL SECTIONING

In the centuries following Hooke's investigations, sectioning biological specimens became conventional. When Normal Wessells was compiling *Biology* (1998), jointly authored with Janet Hopson, he took a picture of a cork section to show the structures of which Hooke had written. The section was cut in a modern laboratory sputtered with gold in the conventional manner and imaged under a state-of-the-art scanning electron microscope magnifying about 600X. It is a good image — but Leeuwenhoek's sections, dating back more than three centuries earlier, give better results. Sectioning has been at the heart of biological microscopy ever since.

On April 2 1686, Leeuwenhoek wrote a letter that



Leeuwenhoek cut dried specimens when examining bovine optic nerve under his microscope. He called these “slices” (rather than “sections”) because they lacked finesse. However, they still reveal the essential anatomy of the nerve, and the space between the dura and arachnoid layers can be clearly discerned.

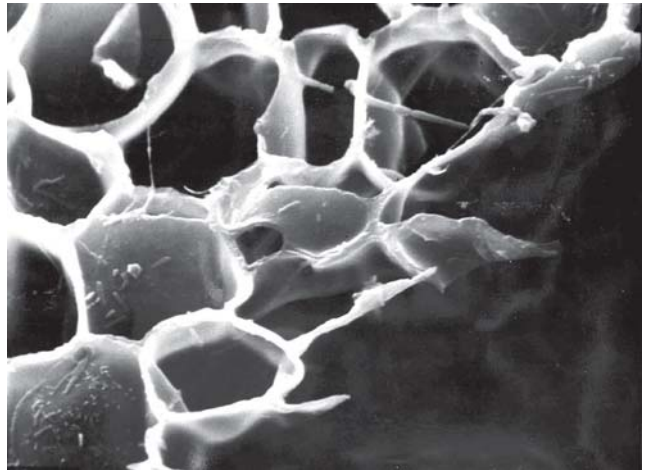
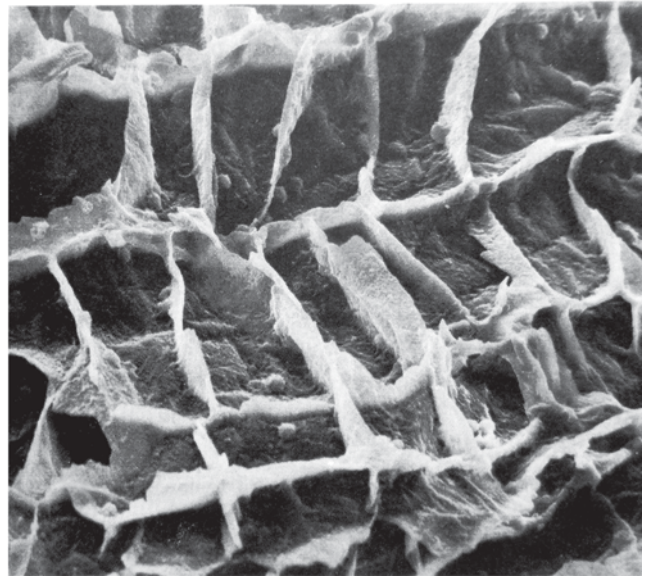
described two more new techniques: microdissection and serial sectioning. He wrote: “I have thought fit to put some cotton seeds — which I have had by me for over a year, and which are so old that their greenish color has already faded — in water for one night, after which I removed from them their tough rind, being their first; and then their soft membrane, being their second envelope; and separated the leaves a little from one another. Eight or nine of these seeds, from which the young cotton tree takes its origin, I send you herewith.” The specimens showed his perfection of microdissection, and the minute radicle and plumule that would grow to form the mature plant are well displayed in these ancient relics.

Leeuwenhoek then set out to show how the internal anatomy could be revealed by the ingenious use of sections cut in a series. He took some of the soaked cotton seeds and describes how he “cut one of them into twenty-five to twenty-six round slices, and the other into twenty-eight to twenty-nine round slices, which too I send herewith.” They remain as dried specimens to this day and show us that he fully appreciated how serial sectioning could be used to reveal the internal anatomy of minute specimens. The technique became of crucial importance and is widely used today.

Leeuwenhoek wrote with excitement about his discovery of microbes. He had been voyaging on a local lake named Berkelse Mere and took a sample of the

#### Figure 5-1 RIGID WALLS OF PLANT CELLS.

This specimen, magnified about 600 times, reveals the regular compartments Anton van Leeuwenhoek originally saw in a thin slice of cork. The appearance of such plant materials led Robert Hooke to coin the term “cells.”



Top: In 1998, Normal Wessells used a modern microscopical laboratory to prepare this section of cork as an illustration in a textbook jointly written with Janet Hopson. The section was gold-sputtered and imaged through a scanning electron microscope. Its cut surface is not as clear as that prepared by Leeuwenhoek over three centuries earlier. Bottom: Leeuwenhoek cut this section of cork in May 1674 and mailed it to London, where it lay undisturbed for 308 years until 1981, when the author discovered that it had survived intact. This area is thinner and the cut surface is more even than Wessells’s modern section.

water home to examine under his homemade microscope. In his own words, he observed: "Very many little animalcules, whereof some were roundish, while others, a bit bigger, consisted of an oval. On these last I saw two little legs near the head, and two little fins at the hindmost end of the body. Others were somewhat longer than an oval, and these were very slow-moving, and few in number. These animalcules had various colors, some being whitish and transparent; others with green and very glittering little scales; others again were green in the middle, and before and behind white; others yet were ashen grey. And the motion of most of these animalcules in the water was so swift, and so various, upwards, downwards, and round about, that it was wonderful to see."

## TODAY'S LIMITED VIEW

That is such a vivid description of entrancing little microbes enacting their busy lives in June 1674. Would you like to move forward with me 340 years into the future, to October 2014? Let's turn to the world's most comprehensive source of information and open Wikipedia. We will look for the entry on "protozoa." These are such spectacular organisms that the choice of vivid illustrations is vast, and yet the only picture on the Wikipedia page is of some tiny purple dots representing the parasite *Leishmania* lurking within a leukocyte. This could be the most boring, unrepresentative picture of protozoa ever published.

My much-admired friend John Corliss published his mammoth book *An Illustrated Guide to the Protozoa* in 1985. The 630 pages are richly illustrated with countless detailed line drawings covering more than 3,000 genera. Compare that with today's Wikipedia page on protozoa; at the end of their article they list only four protozoa that readers can consult online: *Ameba*, *Giardia*, *Paramecium* and *Trichomonas*. That's it. Leeuwenhoek described more than that in his first week as a microscopist back in 1674. Wikipedia prides itself on featuring everything, and can be far more up-to-date (and comprehensive) than Corliss's reference book published 30 years ago. The fact that this public resource can be so dismissive of these attractive and important organisms is typical of our age.

So let us look at the most elevated authority we can imagine. We will turn to that edifice of world science, the Royal Society of London. This is where Hooke worked, where Leeuwenhoek sent his letters and where modern science was born. The Society embraces the world's leading scientists and is the longest-living academy of science anywhere. This is where scientific truth

is at a premium. We could go no higher.

Next we will turn to one of the greatest writers of our age, Bill Bryson, a Fellow of the Royal Society. He was elected an honorary fellow for compiling a book, *Seeing Further, the Story of Science and the Royal Society* (published in 2010), commemorating the 350th anniversary the society's royal charter in 1662. Bryson has been chancellor of Durham University, holds the President's Award from the Royal Society of Chemistry, was given the James Joyce Award by University College Dublin, had Oct. 21 renamed "Bill Bryson, The Thunderbolt Kid, Day" in Des Moines, IA, and was recently given an honorary doctorate from King's College London for being "the U.K.'s highest-selling author of non-fiction, acclaimed as a science communicator, historian and man of letters." The Royal Society and Bill Bryson — the perfect combination. Surely, they'd get it right.

Turn to the book's pages about the early days of the microscope. This is not as easy as it seems, for the book lacks any form of index. You cannot find much help from the list of contents either, for the chapter titles are couched in the pretensions of our age ("Archives of Life," "Images of Progress," "Making Stuff" and so on). You will find Leeuwenhoek lurking within Bill Bryson's introduction, and here is Bryson's description of the microscopes. Read it twice — I assure you that I did not make this up: "These were tiny wooden paddles with a little bubble of glass embedded in them." Someone must have complained about the "paddles" because, when a later edition appeared, it had changed. The new version said the microscopes "were little more than modest wooden dowels with a tiny bubble of glass." Let's face it, "dowels" is even worse. However did such ridiculous descriptions pass through strict editing to appear in print?

## THE SINGLE-LENS APPROACH

The simple, single-lens microscope can offer so much. In 1998 I was approached by Professor Heinz Wolff on behalf of the European Space Agency (ESA). The spacecraft designers sought a new kind of microscope that could image living cell aggregates in the microgravity conditions of space, and I produced a prototype that was light and compact. Its final version weighed a couple of ounces and took up no more space than an apricot. The secret was the magnifier: I opted to employ a single lens, for it provided the necessary resolution at the required magnification. The use of an LED for darkfield illumination dispensed the need for a bulky condenser, and we no longer needed

the compound lens systems of the objective and ocular assemblies.

The reason for opting for this principle was to save bulk. There had been other attempts to make portable microscopes, but they all relied on conventional optics. The best was the MacArthur microscope, created by my much-missed friend and mentor John MacArthur. John's first prototype constructed in 1930 had a body built of wood; he made a metal version in 1932. I presented my tiny design at Inter/Micro 1998, and Dr. Walter C. McCrone commented on it in *The Microscope* (46:4, pp 228, 230 and 240, 1998): "The late John MacArthur, whose tiny portable microscope went to the North Pole, to the bottom of the sea, and to high mountains, hoped it would eventually go to the moon, Mars, and beyond. Much as I highly regard John and his microscope, it is very apparent that the European Space Agency went to the right man for their new space scope." This was a proud moment for me and a vindication of the single-lens concept.

Suddenly, others are beginning to show an interest. For the last 20 years, enthusiasm for microscopy has been in the doldrums and standards are often low. The injection of enthusiasm from hobbyists — so evident in amateurs carrying out home experiments with DNA and homemade rockets! — has been lacking. The sudden change has come about because image capture is now universally available: Mobile phones provide the perfect camera for experimenters. For instance, you can buy a microscope adaptor for the Apple iPhone 4 for less than \$20 that magnifies 60X. Thomas Larson of Seattle sought \$50,000 funding online and raised more than \$110,000 to develop his Micro Phone Lens, which magnifies 150X.

In reality, the cost can be minimal. With the widespread availability of smartphones, adaptors are now being marketed for less than \$10, which allow you to use your phone as a microscope. Indeed, you can obtain surprisingly good results without an adaptor; search on YouTube for "kmyoshino" to see one way of harnessing the existing lens of a phone. Meanwhile, Manu Prakash has presented a TED talk on his proposal for the "Foldscope," a 50-cent microscope which folds like origami. It looks exciting, though many of the micrographs they use in presentations seem to have been taken with a conventional instrument and not at all with the Foldscope.

Experimenters are now using small plastic lenses harvested from a CD reader, and even Leeuwenhoek's aspheric lens has a modern equivalent: Two Australian scientists have produced a single microscope lens



A smartphone can be mounted on a homemade stand to act as a serviceable microscope; a search on YouTube for "kmyoshino" shows how easily it can be done. Inexpensive lens attachments can be purchased that convert phones into microscopes, though this shows that you do not necessarily need the adaptor.

made from polydimethylsiloxane (PDMS) used to make contact lenses. Dr. Steve Lee of the Australian National University Research School of Engineering and Dr. Tri Phan from the Garvan Institute of Medical Research in Sydney have shown that a tiny lentil-sized droplet lens can offer high resolution. To quote Lee: "When I saw the first images of yeast cells I was like, wow!" This may not sound quite as lyrical as Leeuwenhoek's description of living cells from 1674, but we all know what he means.

Meanwhile, the popular accounts of microscopy are submerged under a great wave of errors. If the public wish to review the history of art, European empires, the story of flight, how architecture developed, quantum physics, endangered animals, the history of astronomy or knitting through the centuries, they will find reams of reliable reading matter. But even though biological microscopy underpins our age, the overwhelming pressure is to perpetrate the fiction of amateurs tearing their specimens apart and embedding their lenses in wooden paddles (dowels, sorry). We smile condescendingly at 16th century writers and their feeble grasp of reality as currently construed. But the era of myths and fairy tales is with us still.

The story of the microscope is the single most distorted account of science that any of us has ever seen, yet ways of magnifying our world are all around us. If ever there was a time for a revolution, it is now. Everyone can be a microscopist. Our magical universe is waiting to be offered to the world.