So many amateur opticians have applied their talents to the construction of homemade telescopes that the path is well beaten. Further progress has come to rely more on additional detail than new concepts. To gaze upon the magnified wonders of the heavens does indeed generate a sort of primeval delight, but here the opportunity for original scientific discoveries is limited. How different it is with amateur microscopy!

There are a world of useful discovery in biology remaining to be made by amateur microscopists, but the instrument that is the tool of the trade is invariably bought ready made. The standard prescription for a lay person is to buy a second-hand microscope and then maybe scrimp to buy a first-class objective lens.

The basis for this curious difference in philosophy is partly culture and partly technical. Dedicated amateurs such as Russell Porter and Albert Ingalls set an immortal standard for technical excellence in the field of amateur astronomy. This legacy has drawn generations of gifted amateur astronomers who remain a strong and active group, and a source for the major basis for support of such publications as *Sky and Telescope* magazine. The technical basis for the lack of a corresponding interest in amateur microscopy actually has much to do with the nature of the lens.

Astronomy is based primarily upon a large concave mirror that can be easily ground by amateurs at home with the simplest of equipment. Even a mediocre mirror grinding technique gives passable results that can be continually refined with skill, experience, and a modest investment in technical accessories.

In contrast to astronomy, microscopy has been retarded in its progress by the difficulty of making a good short-focus lens, the troublesome counterpart of a telescope objective. The short-focus lens is even today one of the most difficult optical surfaces to accurately generate. It is generally a tiny glass hemisphere


## Summary

*In but a few hours, an amateur scientist can construct a pocket microscope that will make visible the details of insect structure and even living bacteria. Such inexpensive, high-power microscopes have practical uses ranging from field research to medical research in developing countries.*


# The Homemade MICROSCOPE

By Roger C. Baker Jr.

Photograph by George H. Mayer

# The Homemade MICROSCOPE

forming the front lens of a microscope objective. Anton van Leeuwenhoek (1632-1723), the famous Dutch maker of microscopes, was the first to discover a means of grinding even smaller high-power lenses, but he kept his techniques secret. Contemporary optical artisans are nonetheless able to make similar lenses with simple, traditional equipment.

Given this fact, it is strange that few investigators have sought to duplicate the optical technology that allowed Leeuwenhoek to discover bacteria with a simple hand-held microscope. The following discussion attempts to help fill this conspicuous technical gap. True, it is probably not practical to handcraft a lens with the full capabilities of a good color-corrected, oil-immersion objective. One can, however, come reasonably close for only a few dollars and end up with something that can be slipped in the pocket and is also fun to build.

The path of exploration described in the pages that follow is based on both simple and compound objective lenses used without an eyepiece lense. Such lenses, when they are held close to the eye, are the basis for compact, high-resolution microscopes of the sort that Leeuwenhoek used. Lenses used in this way give a very bright and clear image, superior in some ways to that of a conventional microscope. Microscopics should strive for better resolution rather than greater magnification. A large but dim and fuzzy image is no improvement over a small bright clear image.

The Holy Grail of amateur microscopy might be considered Leeuwenhoek's feat of observing well-defined bacteria darting about in a sample of water. The limit of resolution of a simple spherical or biconvex lens is about one micrometer, just sufficient to reveal many bacteria as fuzzy moving specks. (One micron is one millionth of a meter or one thousandth of a millimeter. One inch is 25.4 millimeters.) The resolution needed to observe bacteria with some clarity, about one-half micron, is not possible with a single lens. Instead, two lenses are required. They form what is known as the compound objective lens.

## The Options in Lens Design

To understand why compound lenses are necessary for the best resolution, we must first understand that the resolution of even the most perfectly shaped microscope lens is limited by the angle of the cone of light (Figure 1) that it is able to gather from the object being viewed. The larger the angle of the cone at its apex, the more light gathered. This relationship only became clearly understood after 1873 when Ernst Abbe, a German optician, published the theory linking numerical aperture, the measure of this angle, and the theoretical resolution of microscope objectives. The larger the angle, the greater the aperture and the better the resolution. The theory states that the maximum resolution of a lens is proportional to its numerical aperture divided by its light wavelength. To improve resolution further, we have a choice of two directions to follow. We can either increase the numerical aperature or shorten the wavelength of light we use.

An increase in the numerical aperture can be accomplished with a pair of lenses, known as a compound-lens objective. Amateurs can achieve good results with a combination of two plano-convex lenses, further assisted by the use of the *immersion principle* described below.

Compound objective lenses with high-numerical apertures generally take the form of a hemispherical plano-convex front lens mounted with its flat side toward the object to be viewed and one or more lenses of lower power mounted above, toward the eye. Even if the front lens is incapable of completely bending the cone of light completely inward to create a focused image under these conditions, the second lens mounted close above it can complete the job. Such a combination acts to shorten the effective focal length of the front lens, thereby allowing it to capture a wider cone of light. This increases the resolving power of the combination.

When the greatest magnification is not required, single lenses are appropriate. These may be spherical, biconvex or plano-convex. It is physically impossible for a single lens to resolve details smaller than about one micron. sufficient to observe living bacteria but not very clearly. When they are spherical, such single lenses tend to have a narrow field of view; in other words a clear zone in the center of the viewing area surrounded by a blurry peripheral region. Nevertheless, a pocket microscope with such a single spherical lens is very easy to make and is a good first step for the amateur.

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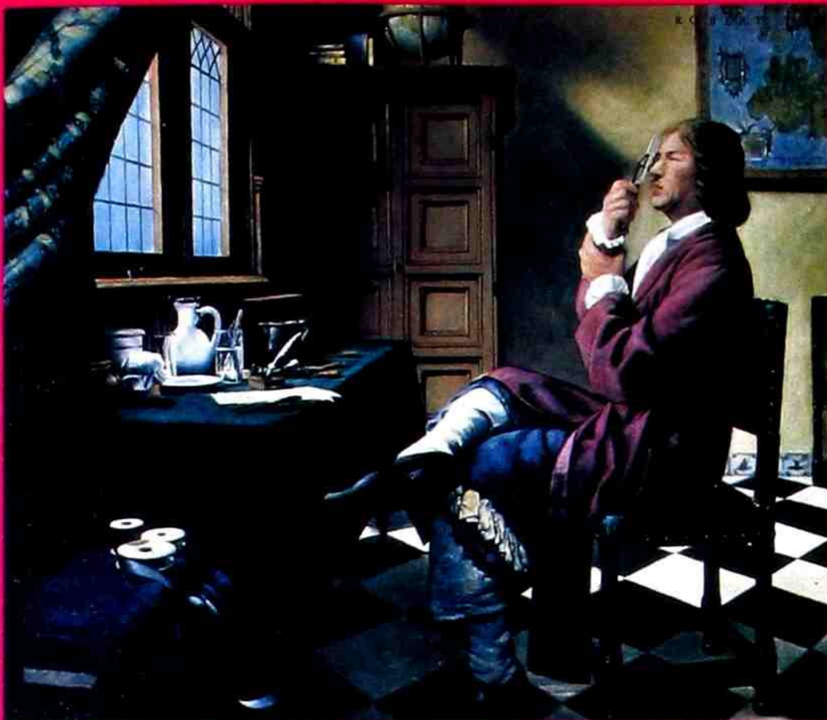
For many purposes, it is useful to enlarge the field of view more than a fully spherical lens will allow. One way to achieve this goal is to start with a glass capillary and blow a biconvex lens. A biconvex liquid glycerin lens is another fairly easy way to give a wide field. Such a lens can also be sealed to give a more or less permanent plano-convex glycerin lens with similar advantages.

The most sophisticated route for the amateur is to grind glass lenses in much the same way that Leeuwenhoek might have done it, according to a method I have recreated. Biconvex and plano-convex lenses ground and polished in this way have the most accurate curvatures and thus give the best results of any method when lenses with a radius of



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The Holy Grail of amateur microscopy might be considered Anton van Leeuwenhoek's (1632-1723) feat of observing well-defined bacteria darting about in a sample of drinking water. This famous Dutch pioneer-maker of microscopes held his high-resolution, compact instrument close to the eye. He kept his technology secret.

curvature of less than about one millimeter are not required. Simple lenses of these types are very suitable for general purposes due to the clear image and wide field whenever the very greatest resolution is not required. The illumination requirements are easily met with a number of simple arrangements.

The most highly curved lenses, which give the highest magnification, are easiest to prepare using the inherent surface tension on a droplet of glycerin or on a tiny bead of molten glass. The surface tension acting on a droplet of fluid forces the droplet into a sphere. The sphere would be perfect if made in space where there is no gravitational pull, or near perfect when the droplet is so small that the surface tension is extremely large for the mass it has to confine. Tiny raindrops are spherical because of surface tension.

The reader may wonder what role the conventional compound microscope plays in this discussion. In addition to the objective lens, this type of microscope incorporates an eyepiece lens and sometimes a field lens mounted along a common axis in a tube. Viewing the image is easy but the instrument is bulky. Our various types of objective lenses could be used in such a microscope, but the image quality ultimately depends on the objective lens, which is our major topic.

## How Compound Lenses Are Made and Used

As we have seen, the greatest resolving power is obtained with a compound lens. Unfortunately, if such a lens is used dry, part of the cone of light entering the lens arrives at too great an angle (the critical angle) is reflected away from the surface of the lens and lost.

For this reason, the very greatest resolving power is attained in high-resolution, compound microscope objectives by the "immersion principle" in which an optical coupling layer of liquid is placed between the object being viewed and the glass surface of the front lens. This significantly increased the numerical aperture of the lens.

If the liquid is an oil with the same refractive properties as glass, the end result is identical to embedding the observed object inside the glass of the lens, enabling the top surface of this front lens to refract and bend inward all or most of the entire cone of light that reaches the surface of the lens. Liquids other than immersion oil, such as water, will work almost as well.

So much for theory. The best results I have achieved so far are from the combination of a small radius, nearly hemispherical, plano-convex front lens, of either the glass or liquid variety, in wet contact with a microscope slide. A second ground and polished plano-convex glass lens of lesser curvature is mounted imme-

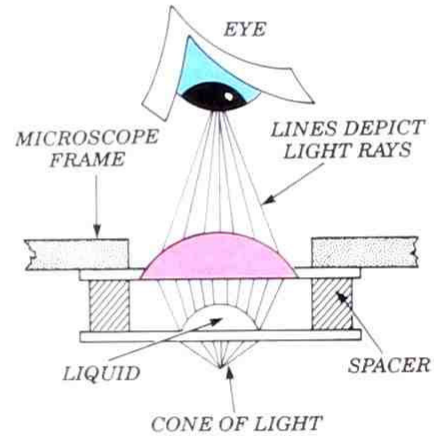



Figure 1. A homemade compound lens assembly.

diately above it with the curved side of both lenses facing the eye. Figure 1 shows this arrangement.

The two lenses are mounted so close that they nearly touch. With the help of a thin metal spacer and a few dabs of silicone rubber, the spacing is maintained. It appears possible to approximately duplicate Leeuwenhoek's best observations with such a lens combination. The practical benefits of a water meniscus beneath the front lens and the slide are due to a complex combination of a decrease in light losses from reflection, a reduction in spherical aberration, and an increase in numerical aperture.

If the plano-convex lenses are both made of glass ground and polished according to a method similar to that Leeuwenhoek used (described below), the radius of curvature of the hemispherical front lens, and thus the magnifying power of the combination, cannot be made so great as when the front lens is a drop of glycerin. It is not hard to make a glycerin hemisphere about one half millimeter in diameter, whereas a corresponding glass lens cannot be made less than about two millimeters in diameter. Therefore objects such as bacteria are easier to observe with a compound lens using glycerin for the front lens as shown in Figure 2. For those with good eyesight, the resolution is equally good when both lenses are glass. Either alternative is satisfactory. It does not appear possible to get good results when the larger lens is made of glycerin. The increased diameter and mass of the glycerin cause the hemispherical surface formed by surface tension to be deformed by gravity.

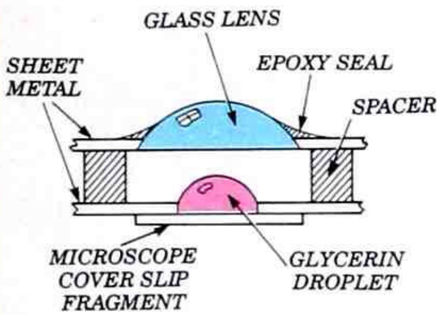


Figure 2. A compound lens with a glass element and a glycerin element.

A good test for comparing the resolving power of any of these lenses, wet or dry, is a thin smear of one part each of blood and India ink on a microscope slide protected with a cover slip glued on top with five-minute epoxy. Under these conditions, the blood corpuscles appear as clusters of sharp-edged clear discs averaging 7.2 microns in diameter against a gray background. A more traditional optical test used by professionals is the resolution of detail in the silica skeletons of certain diatoms. Epoxy is a useful substitute for Canada balsam to permanently mount anything from small insects to stained cells. The details of preparing such specimens is a subject for another time.

Another good test material can be prepared the same way that Leeuwenhoek did. Simply mix a little pepper as he did, or for that matter almost any other food material, with water, wait several days and the liquid will teem with living, moving bacteria.

The best observing conditions for a high-power, compound immersion lens require a wide-angle light source. This might be a convergent beam such as a light bulb or even a candle focused with a condenser lens. Alternately, it might be a wide-angle diffused light such as a nearby fluorescent lamp and a tilted mirror to pass the light upwards through a microscope clamped in a stable position. The specimen is generally immersed inside a wet layer under a cover slip and a drop of water as the immersion fluid is carefully placed on the cover slip before the lens is lowered into focus with the screw adjustment.

## Unwanted Color

Chromatic aberrations that arise because lenses act as prisms that produce unwanted color spectrums along with magnification. For amateurs to fabricate their own achromatic objectives from scratch appears to be impractical. Fortunately, single lenses or even compound objectives do not appear to suffer as seriously from this problem as they would if they were incorporated into compound microscopes. In fact, single lens-microscopes outperformed fully achromatic compound microscopes until the 1830's. It is interesting to note, however, that Sir David Brewster sandwiched layers of oil between the plano-convex elements of compound lenses to give fully achromatic objectives. This approach was discarded early in the nineteenth century, primarily because it was messy, but it does suggest the range of unexplored technical possibilities that await the amateur.

A much easier way to reduce chromatic aberrations is to use a filter to remove much of the low-resolution red end of the visual spectrum. A spherical flask or clear Christmas tree bulb filled with a blue solution of copper sulfate should work well as a combination light condenser and filter.

## How to Make Fused Glass Lenses

A flame will fuse the ends of glass filaments into spherical beads. These tiny spheres are very easy to make and can be used as fairly satisfactory lenses with a maximum resolution of about one micron.

Fused glass lenses are so easy to make and so prone to minor defects of curvature, bubbles, and striations that it's best to make a number of them, and then select the best ones. Begin by

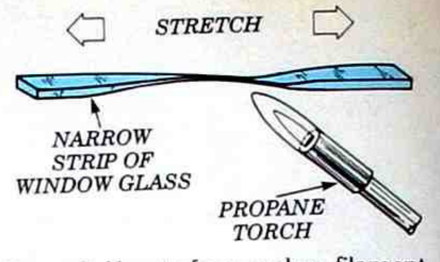


Figure 3. How to form a glass filament from a narrow strip of window glass with the help of a propane torch.

using a propane torch to soften the middle region of a section of clean thin glass, such as a glass rod or a thin strip cut from window glass with a glass cutting tool. Then stretch the soft glass into a filament somewhat smaller than the diameter of the desired glass bead as shown in Figure 3. This filament need not be circular in cross-section.

Spherical beads up to 0.15 inch (4 millimeters) in diameter can be made, but these are generally not of high-optical quality. Initial work indicates these may be useful as spherical condenser lenses for compound objectives when they are mounted beneath the light hole of a microscope at an adjustable distance from the slide. To make these larger beads requires that their supporting stem also have a large cross-section.

For the smaller beads of a millimeter or so in diameter which are normally used as lenses, a piece of filament the diameter of a coarse hair and about a foot long is introduced sideways into a small cool flame so that the lower end droops at a ninety degree angle and then fuses into an almost perfectly spherical bead of glass as shown in Figure 4. Break off the bead with a tweezers and continue making beads until you have a dozen or so. A minimum fusion temperature is desirable; too hot a flame frequently leads to defects such as bubbles and striations.

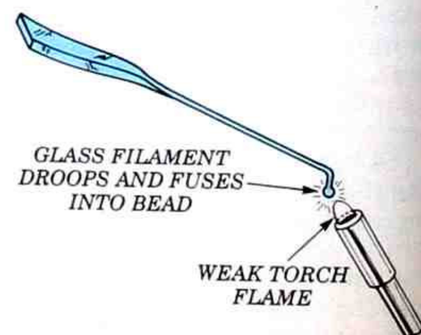


Figure 4. How to form a tiny glass bead from a glass filament using a propane torch.

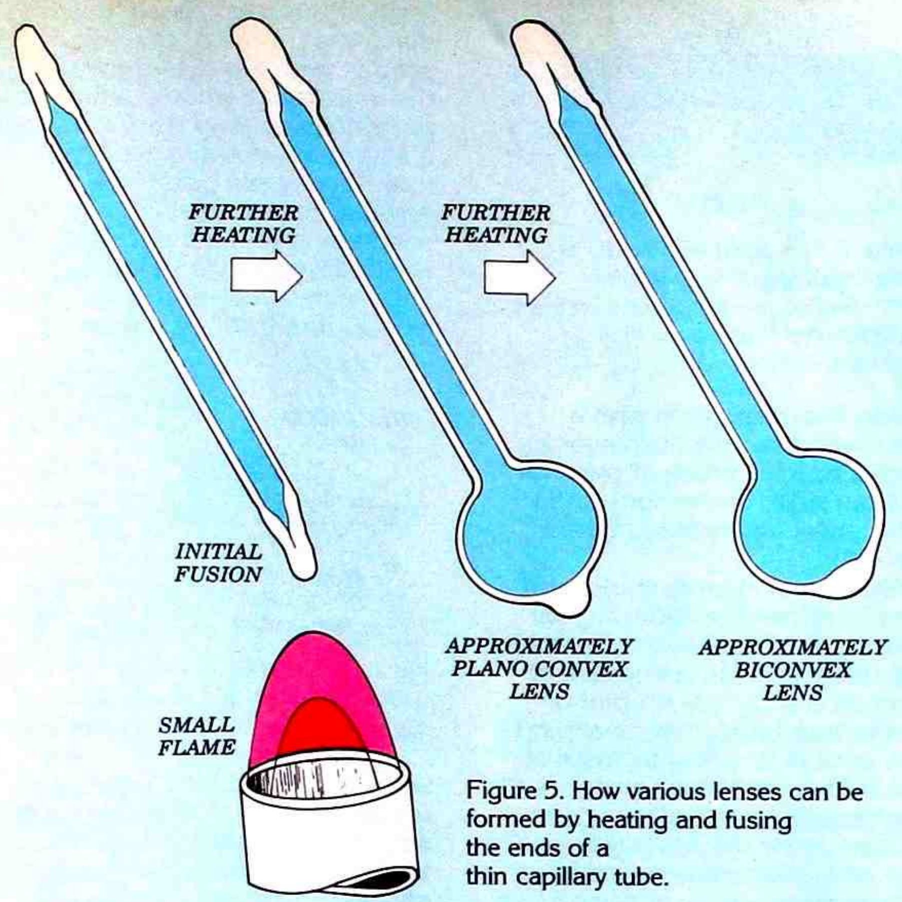



Figure 5. How various lenses can be formed by heating and fusing the ends of a thin capillary tube.

Since the beads are suspended from a filament during fusion, the force of gravity tends to stretch them into a somewhat elongated pear shape, making them astigmatic when viewed through the sides as they must be when the sphere is used as a lens. Smaller beads about one millimeter or less in diameter are less affected by gravity and tend to be more perfectly spherical. Therefore, they work best as high-power lenses.

Clean glass is essential. It is best to clean the glass well before it is drawn into a filament and to avoid touching it until it is fused into a bead. A good test of optical quality is to rotate the bead around its central axis while watching the magnified image of a distant view revealed in the lens for changes or distortions.

One way to make fused glass biconvex lenses is to heat a tube until the end fuses shut, the result being distinctly improved if the tube is rotated in relation to the flame. This process is used to make the integral lenses used on pen-light bulbs. Often these bulb lenses are of sufficient optical quality that they may be broken off and used for low power, single-lens microscopes. J. Van Zuylen (see "Further Reading" listing) duplicated one of Leeuwenhoek's lenses by a similar but somewhat complex process in which a small glass bulb was heated to give a sort of biconvex bead fused into the surface of the bulb. Van Zuylen was also able to show that Leeuwenhoek probably made his smallest and highest resolution existing lens in some similar fashion.

Fortunately, there is a very simple way for amateurs to make these fused lenses, which vary from more or less biconvex to more or less plano-convex. This process of making lenses from glass capillaries is interesting and it takes only a few minutes to get the knack. Everything considered, this is the easiest way to make a passable lens that approximates a biconvex or plano-convex shape. They are variable in shape and quality so it is well to make a number and to select the best.

Start by heating the central portion of a common piece of laboratory glass tubing while rotating it slowly. When it is soft, stretch the tube into a long glass capillary the thickness of a sewing thread. Break off a piece of tubing a few inches long and fuse it shut at both ends in a small flame. As the second end is fused shut, the expansion of the air trapped in the tubing will expand the melted tip into a tiny spherical bulb with the remnants of the fused end remaining as a more or less biconvex bead on the bulb. This is shown in Figure 5. Break off the bead and you will have a lens that tends to have different curvatures on each surface, depending on the exact conditions of heating. See the paper by B. Cohen in the "Further Reading" list in this article for various other possibilities for using the tiny liquid-filled bulbs themselves as lenses and for dark- field illumination.

## How to Make Liquid Lenses

High-quality liquid lenses suitable for microscopic investigations are easily made. Along with the simple glass bead lenses, which are also formed by surface tension, they are an easy and instructive alternative for those desiring to build homemade microscopes. The ease of producing both biconvex and plano-convex liquid lenses with various focal lengths facilitates an insight into the behavior of both simple lenses and lens combinations.

The main problems with liquid lenses are their lack of permanency and the fact that only the smaller liquid lenses tend to have a high optical quality since their surfaces are proportionally less subject to distortion due to gravity. Water, glycerin or other aqueous fluids may be used, but glycerin does not evaporate and is quite suitable despite the fact that it is initially prone to uneven refraction caused by absorption of moisture from the air.

### FURTHER READING

"Antonie van Leeuwenhoek" by T.Y. Kingma in *Boltjes*, Volume 7, 1941 (page 61).

*The Evolution of the Microscope* by S. Bradbury, Pergamon Press, 1967.

B. Cohen in *The Journal of Bacteriology*, Volume 34, 1937 (page 343).

*Modern Microscopy* by V.E. Coslett, Cornell University Press, 1966.

G. Svihla in *The Microscope*, Volume 15, 1967 (page 289).

J. van Zuvlen in *Journal of Microscopy*, Volume 121, 1981 (page 309).

# The Homemade MICROSCOPE

The key to the optical quality of liquid lenses is in the preparation of a perfectly smooth, round hole 0.02 to 0.08 inch (0.5 to 2 millimeters) in diameter faced with a flat rim on both sides in a thin sheet of soft metal such as brass or aluminum. Sheet brass about 0.025 inch (0.635 millimeters) thick from hobby shops works quite well, as does aluminum from soft drink cans.

Begin by drilling or piercing a small hole with a needle in a strip about one centimeter wide with the metal placed against a flat rigid backing. Take care to avoid denting. Then grind both sides of the sheet against #600 silicon carbide paper placed on a flat surface. Insert a gradually tapered steel or glass implement, such as a steel needle or a drawn out section of glass tubing, inside the hole. Rotate this tool under slight pressure so that the hole is enlarged slightly and a burr is raised around its rim as shown in Figure 6. Grind away the burr with carbide paper against a flat hard surface to give a perfectly flat circular rim around the hole as shown in Figure 7. Rubbing the strip against a piece of finely ground glass works even better. Repeat this procedure on both sides until the polished rim of the hole appears flat, round, and perfect on both sides under magnification.

The hole must next be cleaned and the metal surface coated with a thin layer of paraffin so that the glycerin will "bead up" with the perimeter of the bead accurately defined by the edge of the hole. Rub both sides of the hole against a piece of clean paper towel and pull a thread through the hole to clean it. Next,

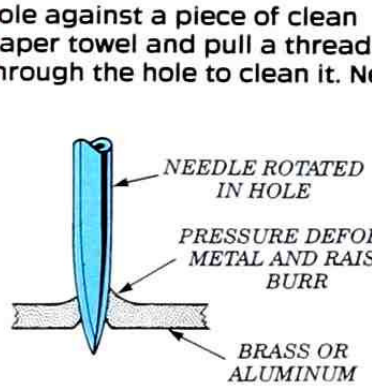



Figure 6. The first step in making a liquid lens is to form a perfectly circular hole with a raised edge in a thin metal sheet.

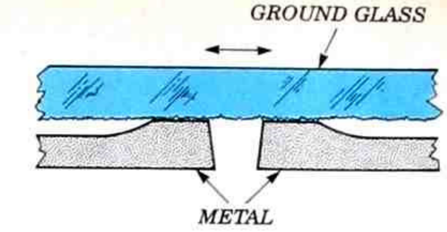



Figure 7. The liquid-lens holder is completed by grinding away the protruding edges of the burrs on both surfaces after making the hole illustrated in Figure 6.

grasp the brass strip with a tweezers, heat the strip over a flame, touch a piece of paraffin to both sides of the hole, and blow away any excess melted paraffin.

Dip a clean needle in glycerin and withdraw it rapidly so that you capture a small droplet on its tip. Use the tip of the needle to deposit a biconvex droplet of glycerin into the hole, sweeping any excess to one side. Inspect the reflection of both surfaces of the droplet, especially near its edges, under about 20 diameter magnification. You may need to adjust the quantity of glycerin so that the drop bulges outward on each side precisely from the rim of the hole as shown in Figure 8. If

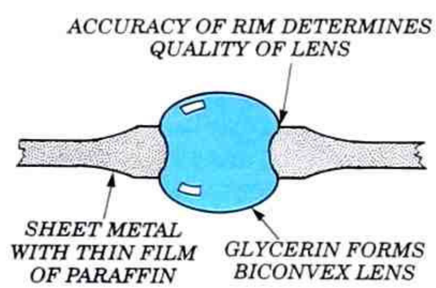



Figure 8. A biconvex liquid lens made from a drop of glycerin.

the magnified reflection from the droplet appears wavy (except very near the edge), it is probably necessary to refinish the hole.

The magnifying power of a glycerin lens can be adjusted by adding or withdrawing liquid with the point of the needle. Such biconvex lenses are easily made and generally give good results with a wide field of view and a resolution of about one micron, provided that their diameter is small and they are maintained in a horizontal position. If left unprotected, however, they collect particles of dust that degrade their optical properties.

It is almost as easy to make a plano-convex lens in a similar fashion. Such lenses are made by placing a fragment of microscope cover slip over the hole in the metal strip when the melted paraffin is applied. This results in a small cavity with a glass bottom. The excess paraffin is scraped out of the cavity with a needle and liquid detergent and washed with water before being filled with glycerin to form the lens. Figure 9 shows the result.

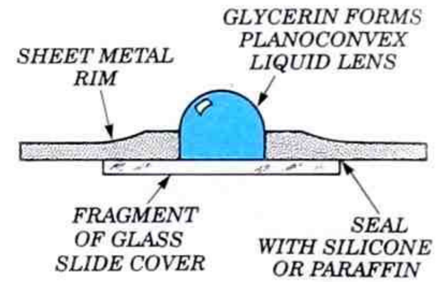



Figure 9. A plano-convex liquid lens uses a fragment of a glass slide cover slip to form the flat surface of the lens.

Such lenses can be capped and rendered more or less permanent with a thin washer like metal spacer and a cover made from a microscope cover slip glued on top with a little carefully applied silicone rubber as shown in Figure 10. They may also be mounted under larger glass plano-convex lenses to give compound lenses as described earlier and shown in Figure 2.

## Leeuwenhoek's Lenses: A Modern Approach

The following account does not represent the last word on the subject. There are doubtless many refinements waiting to be discovered. It can be said, however, that the procedure that follows, which resulted from considerable trial and error, will permit one to grind high-quality miniature lenses.

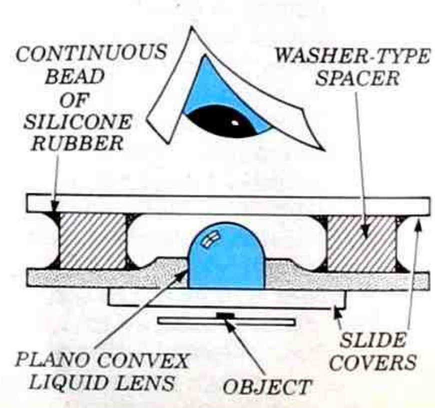



Figure 10. A sealed plano-convex liquid lens will not be contaminated by dust particles.

The first step is to mount a lens blank on the end of a section of hobby store brass tubing about a tenth of an inch (several millimeters) in diameter and about 4 inches (10 centimeters) long. Attach the lens blank to the end of this *lens spindle* with melted dopping wax, a shellac-based material similar to sealing wax which is sold by lapidary shops.

A suitable lens blank might be any clear fragment of window glass that has been roughly shaped to the proper curvature of 0.04 inch (1 millimeter) or more in radius on one or both sides. One of the best ways to do this is to mount the glass blank on the spindle with dopping wax and then run it back and forth with coarse abrasive slurry in a copper channel as the spindle is slowly rotated.

You can make a copper channel by hammering a steel wire of the proper diameter into a strip of annealed copper resting on top of a groove in a soft pine board. Plano-convex lens blanks are roughed out of tiny squares cut from window glass with a glass cutter. Mount them with wax against a tiny plate soldered like a nail head against the rim of the brass tube. Fortunately, ordinary window glass is usually flat to within a fraction of a wavelength of light over such a small area.

Make a pointed pivot from a stout needle with a blunt point. Insert it into the opposite end of the tubular lens spindle and fix it in place with solder, glue or dopping wax. This pivot causes the tube to rotate automatically at an angle to the vertical axis of the rotating tubular tool. Figure 11 shows how the spindle's pivot can be seated in a small, conical indentation punched in a leaf spring such as a hacksaw blade clamped to lightly press the lens spindle against the rotating tube with a few grams of constant pressure.

Since the lens is very small, only a small amount of glass needs to be removed, and grinding occurs rapidly. Thus it is not quite so necessary to use the long series of graded abrasives that larger lenses require. It is possible to grind and polish small lenses in a reasonable time with #120/220 silicon carbide roughing in the channel; #600 grade silicon carbide for initial grinding against the tube; and 5-micrometer alumina or finely graded emery

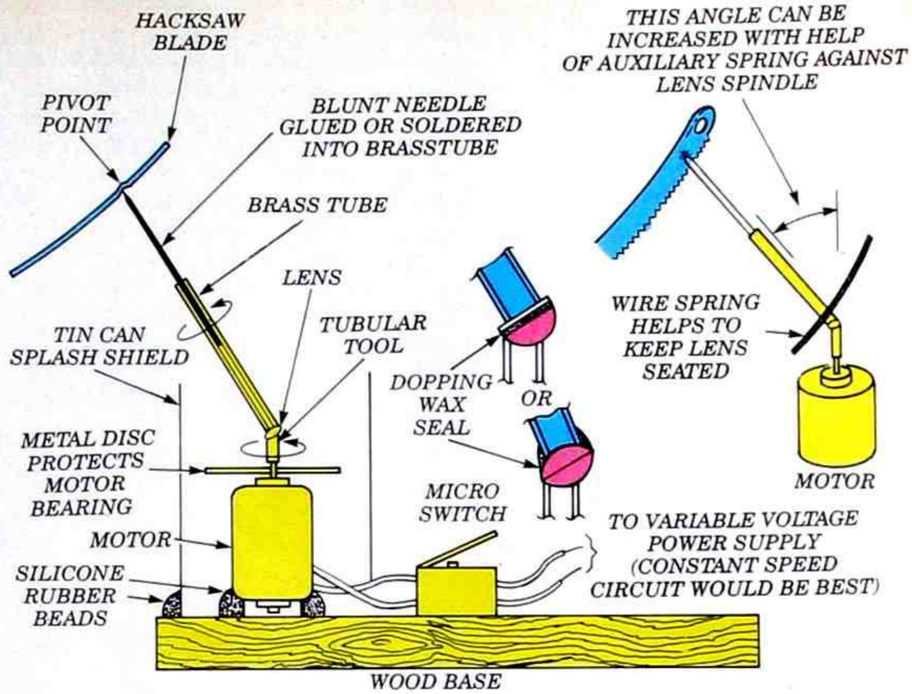



Figure 11. How to assemble and use a simple apparatus for grinding glass lenses. (See text for details.)

powder for final grinding. An oil based diamond composition should be used for final polishing. The abrasives are all prepared by mixing them into a slurry with vegetable oil.

Mount the tubular grinding tool on the shaft of a small DC hobby motor. The motor itself should be mounted on a small board with the shaft extending vertically upward. A few dabs of silicone rubber will hold it in place. A 0.4-inch (1-centimeter) length of small brass tubing about 0.04 to 0.1 inch (1 to 3 millimeters) in diameter (⅔ the diameter of the lens) should be carefully soldered onto the end of the motor shaft so that it is accurately centered along the rotational axis of the shaft. Brass tubing is available from hobby and craft shops.

Use silicone rubber to attach a small perforated copper disc at the bottom of the shaft just above the motor. This will keep abrasive from falling into the motor bearing. Use a variable voltage DC power supply with a convenient switch to power the motor. Make a splash shield to catch flying abrasive slurry from a short section of a sheet metal cylinder such as a tin can. Mount the shield on the board so that it surrounds the motor and extends just above the top end of the tube.

Now you can begin to grind a lens. First, rough out the hand held blank by running it back and forth along the length of the copper channel with #120 carbide slurry while twisting the blank at a constant rate. After the convex blank is wiped clean, begin the fine grinding. Touch the lens blank to a little of the #600 carbide slurry. At first, set the motor to rotate at a fairly low speed while the lens blank mounted on its spindle is held in your hand at an angle from the vertical. Press lightly against the rotating tube while twisting the lens spindle between your fingers. Soon, the lens blank and the inside rim of the brass tube will begin to develop matching spherical surfaces. Once these curvatures are established, set the lens spindle in place to rotate automatically. Periodically, apply a little abrasive slurry to the zone of contact with a toothpick. The angle of contact between the tool and spindle must be such that the center of the lens spindle rests against the rim of the tube, or a circular island of unworked glass will be left in the center of the lens.

Avoid using high pressures and high speeds during the various grinding stages to speed up the process. Too much pressure tends to cause deep scratches, lopsided wearing of the brass tube, and an uneven curvature to the finished lens. High speeds cause vibration and chattering. Fairly low speeds and low pressure during the grinding stages give the best results. During the polishing stage a higher pressure gives the best results. It appears likely that the optimum conditions during each stage are such that the film of abrasive or polishing compound is squeezed just thin enough that a single layer of particles is present between the glass surface and the brass tool, a condition that is a function of speed, pressure, and particle size. If the beveled inside rim of the tool wears unevenly, it can be dressed by increasing the motor speed and pressing the corner of a file against it.

Periodically, remove the glass, wipe it clean for inspection under magnification, and add fresh abrasive. The 5 micrometer alumina should give a semi-polished appearance. When the glass surface appears to be completely spherical with a uniform, velvety finish under magnification, it is ready to be polished.

Polishing materials such as iron oxide may be used, but, in any case, the material should be refined to remove all but the finest particles. One way to do this is to stir the fine dry oxide powder with vegetable oil in a small glass container set in a pan of boiling water. Allow the larger particles to settle out until a clear upper layer forms. Remove part of the uppermost layer of the settled suspension with an eyedropper and deposit it on a piece of blotting paper or unglazed tile. The excess oil will be absorbed, leaving behind a thick, mud-like residue of the finest polishing compound and oil.

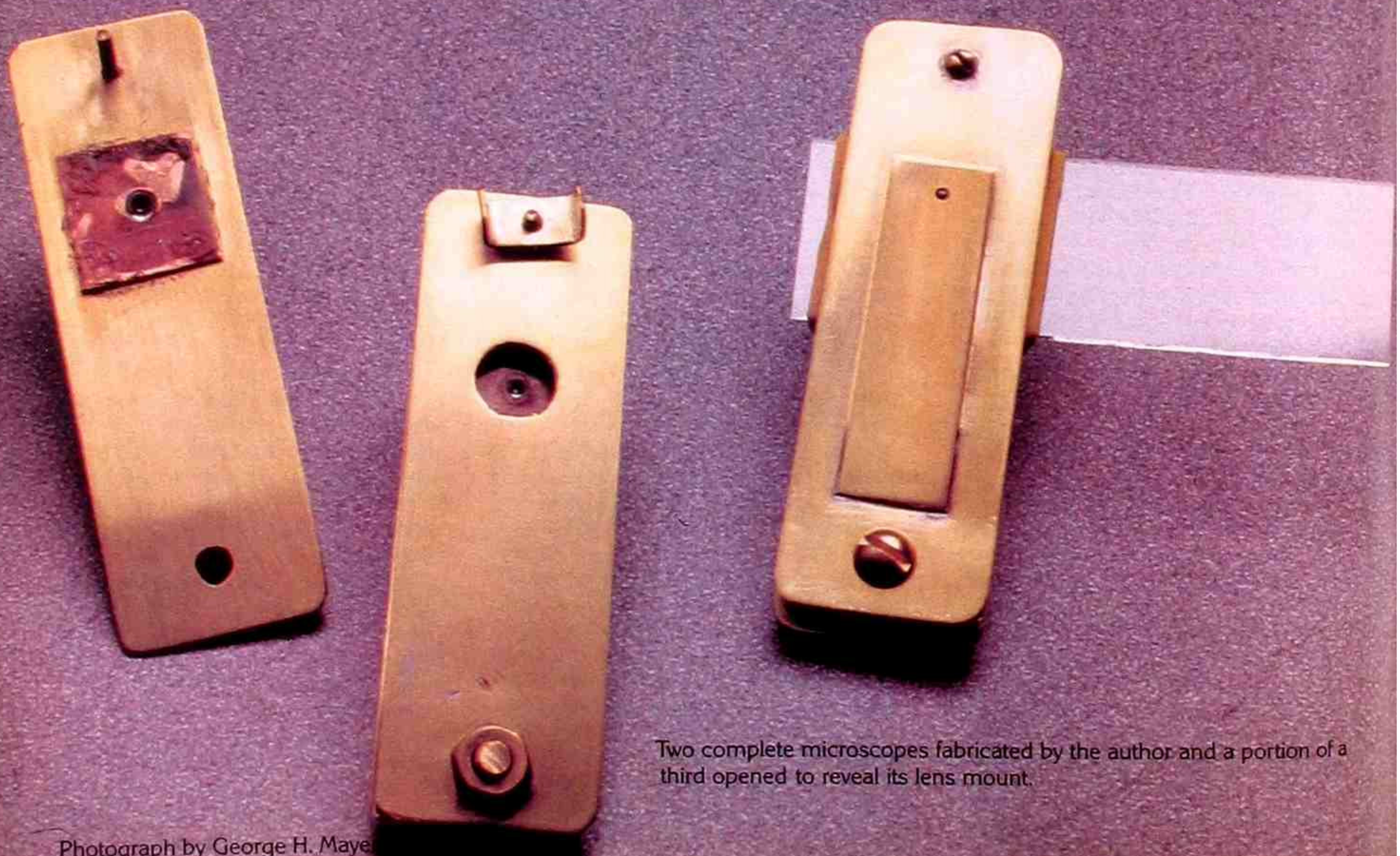
You can save time by polishing the lens using the 100,000 mesh equivalent grade of oil-based diamond paste sold in small syringes for less than $10 by lapidary shops. This works best of all. Only a very small amount of polishing compound is required in any case.

The polishing stage demands careful attention and takes longer than any of the grinding stages. First, apply a dab of polishing compound to the lens and set the spindle in place so that it is held by a greater pressure than used for the grinding stage. Adjust the motor voltage just enough to give a moderate speed of rotation without vibration. The lens spindle will rotate automatically and at the proper angle if the rim of the tube presses against the center of the lens as described previously.

If the lens is a small hemisphere, as is desirable for the front element of a compound lens, you must increase the angle of contact of the spindle to perhaps, 45 degrees. At this angle it is difficult to keep the lens seated inside the rim of the rotating tube. One alternative is to arrange for a second spring to press against the rotating shaft of the lens spindle near the lens so that it remains properly seated. An easier way that works fairly well is to hold the lens against the rotating tube at the proper angle with a steady pressure as you rotate the spindle at a constant speed with your fingertips.

Frequently remove the spindle, wipe it clean, inspect it, charge it with fresh grinding or polishing paste, and resume work until the glass is polished over its entire surface. With practice, it is possible to grind and polish a lens surface in less than an hour. Small curvatures are harder to make but can be polished more rapidly.

A good test of the optical quality of a miniature lens during the polishing stage is to view the



Two complete microscopes fabricated by the author and a portion of a third opened to reveal its lens mount.

Photograph by George H. Mayer

highly magnified reflection of a light source while slowly rotating the lens spindle. The polishing process may tend to leave a few scratches or pits around the edge of the lens, especially when it is highly convex, but these flaws generally cover a small percentage of the total area and are not a serious problem.

When fully polished, warm the lens to remove it from the spindle and rinse it with acetone or nail polish remover to remove excess dopping wax. If it is to become a biconvex lens, remount in the reversed position and repeat the entire process.

## The Microscope Frame

All the parts for a microscope can be fabricated with nothing more than a jeweler's saw, a hand held drill, and a little soft solder. Whichever way you make the lens, a convenient way to mount the lens for practical microscopy is to place it toward one end of a strip of 0.035-inch (0.9-millimeter) thick brass around 4 inches (10 centimeters) long and 1 inch (2.5 centimeters) wide. Bolt one end of this strip to a similar strip of brass with a metal spacer separating the two by a tenth of an inch or so (a few millimeters) as shown in Fig. 12 and 13. This second strip has a 0.4-inch (1-centimeter) hole opposite the lens. Loop a small rubber band under the brass strip and up over both ends of a microscope slide. This will hold the slide in an adjustable position above the light hole, opposite the lens.

Solder the head of a fine-threaded screw to the end of one strip. Insert the screw through an oversized hole in the other strip and secure it with a wing nut. Screwing in the wing nut causes the brass strips to flex inward and focuses the lens onto a microscope slide.

You now have a miniature, high-power pocket microscope suitable for basic investigations indoors or in the field. For practical purposes, it may be best to make several such microscopes, *e.g.* a lower-magnification microscope fitted with a biconvex lens of the Leeuwenhoek type for general field work as well as a high-resolution microscope with a compound liquid immersion lens for the examination of thin layers on slides under cover slips.

Both biconvex and spherical single lenses are generally

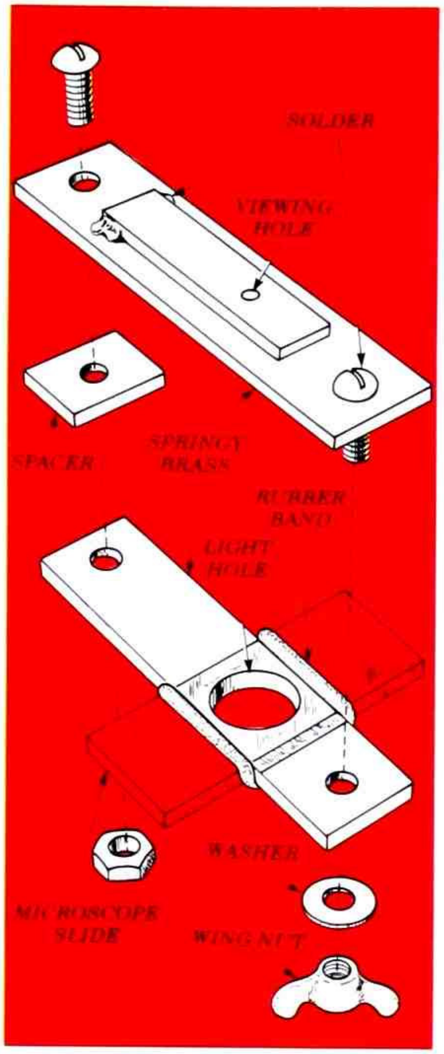



Figure 12. An exploded view of a handcrafted microscope that an amateur scientist can make.

mounted, as Leeuwenhoek did, by mounting them between two thin metal sheets provided with holes slightly smaller than the diameter of the lens and beveled on the inside. One of these is the brass strip that constitutes part of the microscope frame together with a second perforated brass strip. The two are joined with solder at the opposite end so that they may be sprung apart slightly to insert the lens (Figures 12 and 13). Such apertures prevent peripheral light rays that suffer the most spherical aberration from

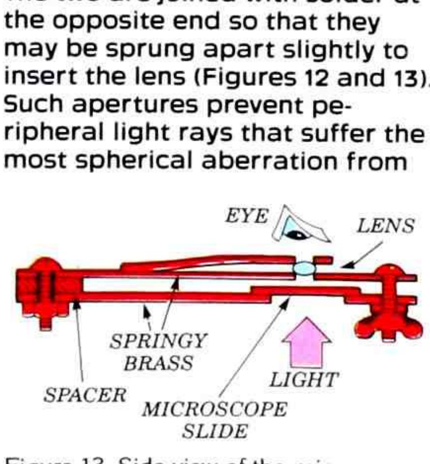



Figure 13. Side view of the microscope. Note the wing nut that controls the focus.

passing by the edges of the mounting holes.

A good way to make perforated metal mounts that fit against these lenses is to take the metal sheet and make a dimple with a punch or nail point. File down the projecting opposite side of the dimple until the metal is so thin that it can be perforated easily with a sewing needle or awl to give a round hole of the required size. This hole then has a bevel on one side that rests against the curvature of the lens. Figure 14 shows this kind of lens holder.

On the other hand, if you wish to mount a plano-convex lens, say for a compound objective, a thin sheet metal support about 0.4 inch (1 centimeter) across is provided with a flat circular hole which closely fits the perimeter of the lens. The metal is placed on a piece of Teflon and the lens is placed inside the hole, flat side down. A little five minute epoxy mixed with a dark opaque filler is spread around the edge of the glass where it fits against the hole. After the epoxy has set, the mounted lens is moistened with water and any excess epoxy is carefully scraped off the glass with a needle or sharp knife under magnification.

Compound objective lenses can be built up on the underside of a hole in the upper brass strip of the microscope frame using a little silicone rubber and metal strip spacers between the pieces of sheet metal holding the two lenses.

## Going Further

The full limits of what amateurs who build their own microscopes can achieve has hardly been explored. This article merely points out a few of a wide range of

### SAFETY PRECAUTIONS

**Always use caution when working with glass.** Protect your eyes with safety goggles, especially when scribing, cutting and breaking glass. Small shards of glass and bits of capillary tubing can easily form invisible but painful and difficult-to remove splinters. Carefully remove and dispose of all glass fragments. Store unused glass away from children. Be especially careful when heating glass with a flame. Wear protective gloves and be sure no flammable materials or chemicals are nearby. If possible, store tanks of compressed flammable gas outside the home.

# The Homemade MICROSCOPE

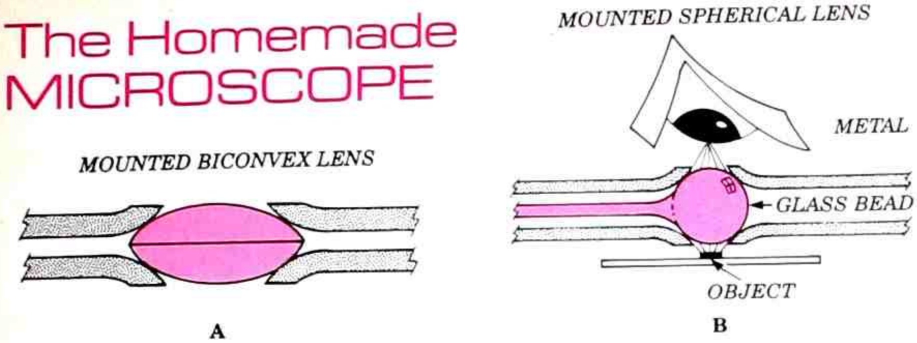



Figure 14. A simple mounting method suitable for a glass bead spherical lens (left) and a glass biconvex lens (right).

**possible options for amateur microscopists. You can enter this neglected and fascinating field of optical experimentation using simple, inexpensive materials** and improve on the methods described. So let us give the amateur astronomers a little competition!

For example, the most sophisticated techniques to maximize the numerical aperture of a lens permit an optical microscope to achieve a resolution of one-half wavelength of light or about one-fifth of a micron. To push the limits even further, one must turn to ultraviolet microscopy.

It is conceivable that advanced amateurs could grind their own short-focus quartz lenses (glass does not transmit ultraviolet well) and use them with glycerin or castor oil immersion fluid to photograph high-resolution images of chromosomes, etc. The ultraviolet could be from a mercury-vapor lamp or even a tungsten-halogen quartz lamp filtered through a silver film chemically deposited on the quartz lens. Such silver films have an ultraviolet transmission window at about 315 nanometers (.315 microns). The practical problems of photomicrography are largely a matter of controlling stray light leakage and getting the object focused accurately before the dim enlarged image is allowed to expose the photographic film. ✷

### GLOSSARY

Achromatic—The focal point of a single lens is slightly different for different wavelengths of light. Therefore, a magnified or projected image produced by such a lens is slightly blurred. An *achromatic* lens is a compound lens in which one lens cancels the wavelength dispersion caused by the other.

Biconvex—Both surfaces of a biconvex lens are curved outward so that the center of the lens is thicker than the outside edge of the lens.

Convex—A convex lens is one in which one (plano-convex) or both surfaces (biconvex or double-convex) bulge or are curved outward.

Index of Refraction—The ratio of the sine of the angle of an incident light ray to the angle of the sine of the ray after it has been refracted (bent) by the medium through which it passes. The index of refraction of air is 1.0003, water is 1.3336, crown glass is 1.523, and diamond is 2.42.

Numerical Aperture (N.A.)—A measure of the light collection efficiency of a lens. In a microscope, the N.A. is the index of refraction of the medium between the objective lens and the specimen being viewed times the sine of the half-angle of the cone of light that enters the objective.

Objective Lens—The short-focus front lens or lens combination in a microscope; if an eyepiece lens is also used, the objective lens is closest to the object being viewed.

Plano-Convex—One surface of a convex lens is flat while the other is curved outward.

Spherical Aberation—An optical defect due to the outzone of a spherical lens surfaces having a different focus than the central region.

### ABOUT THE AUTHOR

Roger C. Baker Jr. is an active amateur scientist whose wide ranging investigations and projects have appeared three times in "The Amateur Scientist" in *Scientific American* magazine. His adventures with homemade microscopes began when he learned how to make a simple fused lens from instructions given in the January 1953 installment of "The Amateur Scientist." As he recently wrote, "The miraculous powers of such an easily constructed instrument in the hands of a young boy were an endless source of fascination."