A ONE-DOLLAR MICROSCOPE

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PRESENTATION

In this article I describe the construction of a very simple low-cost compound microscope that will give you a magnification of about 75. As shown in Figure 1, the microscope I describe is one that just about anyone can build. It is a fun project, and it will help you understand how microscopes work. People often think of microscopes as being very intricate and mysterious instruments, but in reality they are not all that complicated. Building this instrument will show you just how simple they can be. This microscope, which will cost you no more than about a dollar or so to build, is essentially identical to the expensive microscopes that professionals use.

Through this project you will gain an appreciation for the need of using corrective optics to reduce the aberrations. Obviously, the performance of this simple microscope cannot be compared with more expensive professional instruments, which will produce much clearer and brighter images. Nonetheless, it should compare well to the low-cost microscopes that are sold in the toy or hobby shops. It is our experience that so called "toy microscopes" are a real disaster because they commonly give little more than diffuse images or shadows. This can cause a young person to lose all interest in these instruments. On the other hand, an instrument of suitable quality has the potential of sparking a young person’s interest and opening up a world of discovery to them. In this article, I have described how to perfect this microscope and, finally, I will present a model suitable for the observation of protozoa. This instrument will cost you only some tens of euro, but the quality of the images will certainly astonish you.

A microscope is essentially formed by two lenses: the objective and the eyepiece which is also referred to as the ocular. The objective forms a magnified image of the specimen and the eyepiece in turn magnifies this image. In another article entitled "From Lenses to Optical Instruments", we explore how lenses and microscopes work. So, if you feel the need to review or learn more about the basics, please consult this article. Other components such as the main tube, the focusing system, the stage, the condenser and the illuminating system complete the microscope. The instrument I present here is called a **compound microscope** because it contains two main optical components: the objective and the eyepiece. A **simple microscope**, on the other hand, comprises a single lens, which is essentially a more or less powerful magnifier. The glass-sphere microscope, which I described in another article of our gallery is such a simple microscope

MATERIALS

To build the microscope you will need the following materials:

- Four lenses from disposable cameras. ***
- One 170 mm-long piece of 24 to 30 mm-diameter plastic tubing with a nominal wall thickness of 2 mm.
- Plastic tubes of suitable diameter to make the eyepiece and the objective (see Figures 7 and 8)
- Plastic tubes used as couplings
- Square sheet of stiff and opaque plastic 1 x 90 x 90 mm for the rotating diaphragm
- Piece of mirror 40 x 50 mm
- Sheet of brass or stainless steel 0.5 x 30 x 100 mm
- Pine 20 x 140 x 150 mm for pedestal
- Pine 20 x 50 x 440 mm for the upright member and two supports
- Pine 10 x 90 x 120 for the stage
- Pine 10 x 40 x 51 for the mirror
- Four self-tapping screws Ø 3,5 x 20 mm for the clamp of supports
- Four self-tapping screws Ø 3,5 x 40 mm for the supports
- Four self-tapping screws Ø 4 x 50 mm for pedestal and stage
- Two self-tapping screws Ø 3 x 10 mm for diaphragm and mirror
- Two self-tapping screws Ø 2 x 10 mm for mirror
- Four adhesive felt diskettes for pedestal
- Black velvet paper for the internal wall of the main tube and to enhance the fluidity of the focusing movement.

*** To build the eyepiece and the objective of this microscope we will use the lenses salvaged from disposable cameras as shown in Figure 2. Once a disposable camera has been used it is taken to a photo shop where the film is removed and the body of the camera is discarded. What we need for this project is precisely what the photo shops throw away. So, go to your local photo shop and ask them for at least four disposable cameras. If possible, try to get four identical cameras. You might also ask your photo shop for some additional camera bodies that you could keep as a reserve.

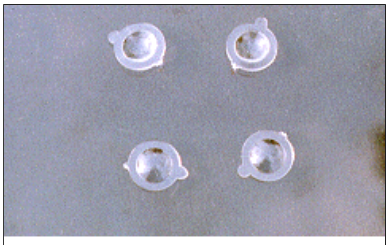

Figure 2 - Objectives of disposable cameras.

WARNING! Do not open disposable cameras that have a flash because you are at risk of getting a severe electrical shock. The circuit that feeds the flash produces a very high voltage, and this voltage may be present even if the camera has not been used recently. For this project you should use only cameras that have no flash.

If, in spite of this warning, you wish to use a camera that has a flash, be very careful. The circuit contains a capacitor which, if it is charged to a high voltage, can give you a severe shock. If you are not familiar with such things, have someone who is knowledgeable in electronics help you open the camera and make sure that the capacitor is discharged. Discharging it may produce a hefty spark, so protect your eyes.

Disassemble these cameras and recover all the lenses you find. Usually, the objective of these cameras is a transparent plastic meniscus. A **meniscus** is a concave-convex lens. Try to find the focal length written somewhere on the camera body. For these cameras it is usually 35 mm. For our project, we will use the main lenses of these cameras. Put aside the smaller and more powerful lenses that are used to magnify the picture frame numbers. You may want to use these smaller lenses later to see if they can be suitable as objective lens.

While removing the lenses, try not to dirty them. To avoid leaving fingerprints on the lenses, handle them by holding them by their edge. You can pick them up by their edge with a pair of tweezers. (Plastic tweezers are best.). You can also use latex or thin cotton gloves. Before you mount them, blow off any dust and clean the lenses with a clean and moist cotton cloth. Do not use paper towels because the paper sometimes includes mineral powders (white clay) that can scratch the surfaces of the lenses. These plastic lenses are very delicate, so try to handle them as little as possible.

MICROSCOPE BODY

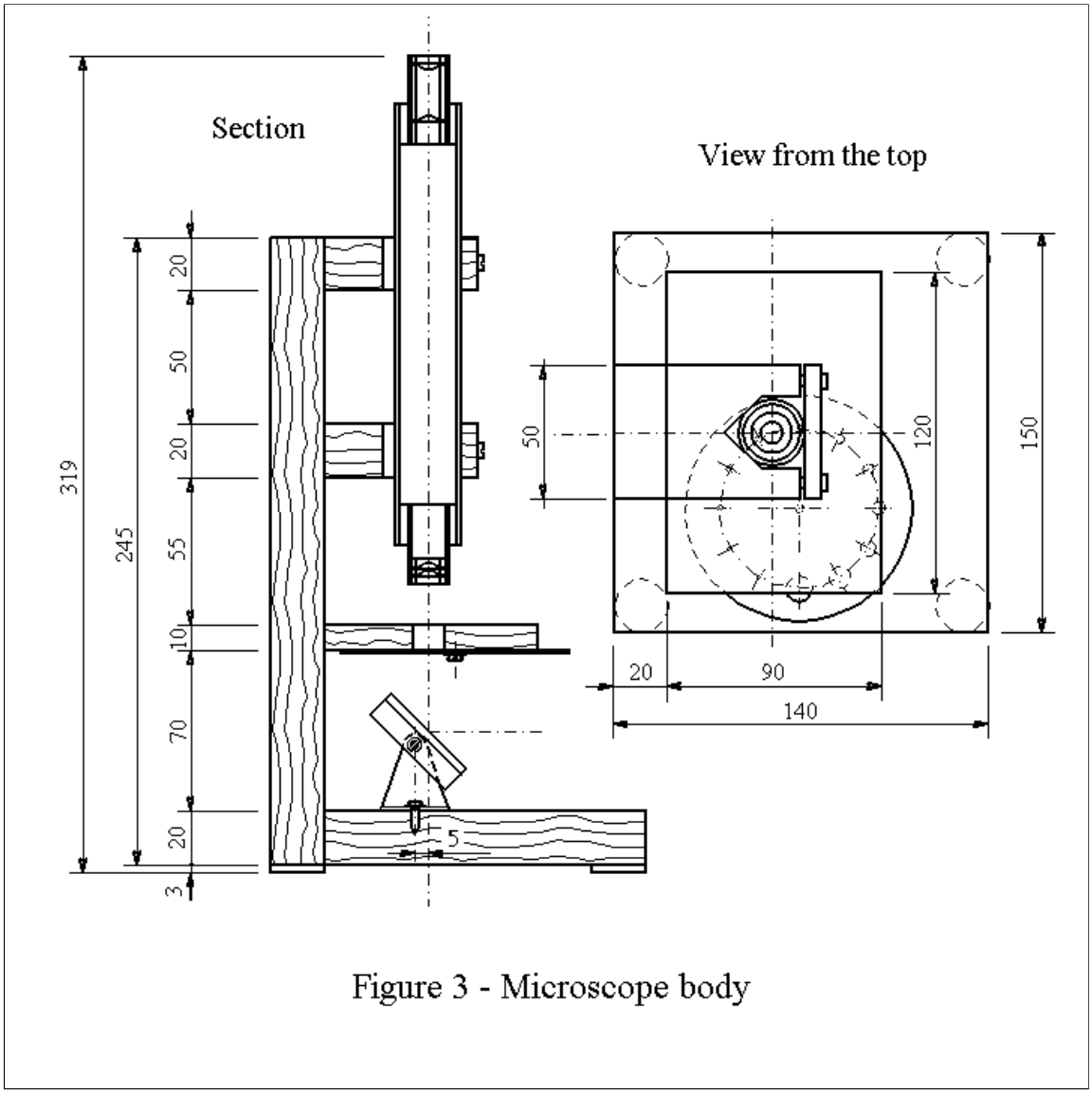

Figure 3 - Microscope body

The body of the microscope provides support for the different parts of the instrument and gives it stability. The body can be built with small pieces of wood joined with screws. Figure 3 shows the structure of the microscope with the principal dimensions. All of the pieces are fixed to the upright member with two screws. Place four adhesive felt pads under the base of the microscope.

BODY TUBE

One of the more important parts of a microscope is the body tube. The objective and the eyepiece are mounted at either end of the tube as shown in Figure 9. The body tube can be made of either plastic (2 mm thick) or metal (1 mm thick). For this project I used a rigid PVC tube for electrical plants. Avoid cardboard if possible because it will wear out in the long run. The outer diameter of this tube should be between 28 and 32 mm. Cut a 170 mm length of pipe which you will have to trim to the measurements given in Figure 9.

SUPPORTS

The body tube is held in place and kept in alignment by two supports. As shown in Figure 4, each support comprises two pieces. The support has a "V" shaped notch and the tube must jut out from the notch by at least one millimeter. The other piece – a small wooden plate – is used to clamp the tube in position. The pressure exerted by this clamp is made adjustable by means of screws. Because wood tends to adhere to plastic and metal surfaces, attach an adhesive velvet strip on the inside surfaces of the two supports and clamps to ease the movement of the tube during focusing. If you do not have any self adhesive velvet fabric you can glue a piece of velvet or thin felt.

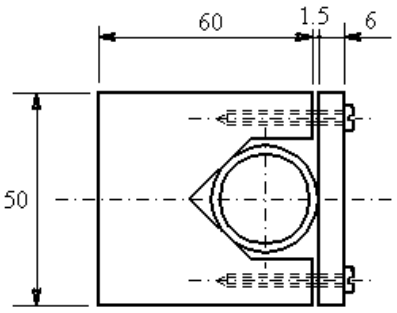

Figure 4 - Adjustable support for the body tube

STAGE

The stage is a piece of wood that has a hole in it to allow light to pass through. To locate this hole accurately, first mount the stage on the upright member and fix the body tube to its supports. Then drop the body tube onto the stage, and with a pencil, draw a circle around the tube. At the center of this circle drill a hole of about 12 mm in diameter. Blacken the inside of this hole with a black felt-tip pen or India ink.

ROTATING DIAPHRAGM

The next step is to mount a rotating diaphragm under the stage. Its purpose is to adjust the contrast of the images. It is a disk of rigid opaque plastic 1 mm in thickness, and it has a series of holes of increasing diameter arranged along a circle as illustrated in Figure 5. Make sure that you drill the holes so that they are correctly aligned under the hole in the stage. To help the disc turn smoothly, mount a flat washer on either side of the disk. Tighten the screw until you are satisfied with the motion of the disk.

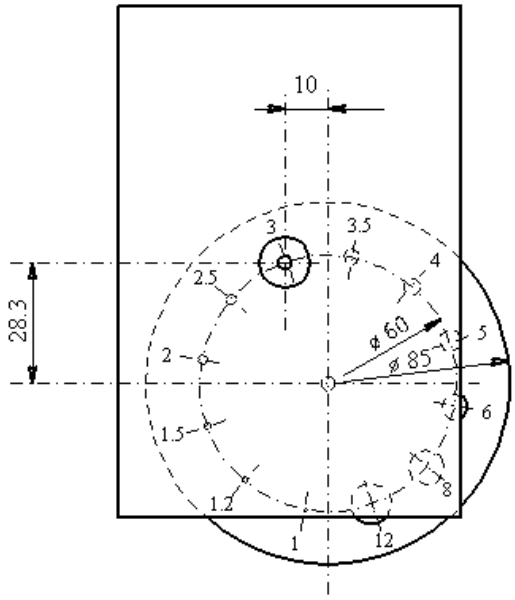

Figure 5 - Stage and rotating diaphragm.

MIRROR

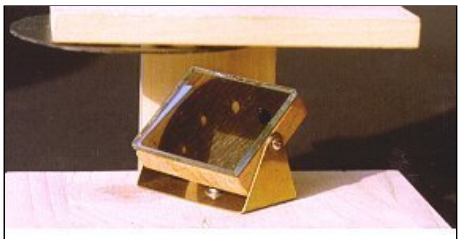

Figure 6 - Adjustable mirror

The mirror is used to illuminate the specimen from underneath. As shown in Figure 6, it is made by a cutting a small rectangle of mirror that is then glued onto a wood backing. The mirror's support is a piece of sheet metal that is bent into a "U". It is screwed to the mirror backing and to the base as shown in the figure. The three screws holding it all together will allow the mirror to rotate in every direction. Adjust the tightness of the screws so that the friction is adequate.

EYEPIECE

The eyepiece serves to magnifying the image formed by the objective. To make the eyepiece we will use two of the four meniscus obtained by the cameras I have mentioned previously. As these lenses all have the same focal length, the eyepiece has to follow the Ramsden

scheme, which is explained later on. Mount the lenses with the convex side turned inward (see Figure 7). The distance between the lenses has to be about 2/3 of their focal length. Hence, if your lenses have a focal of 35 mm, you will have to separate them by 23 mm. Later on we will see how to calculate the magnification of this eyepiece.

To make the eyepiece tube use plastic or cardboard tubes of suitable diameter. The same applies to the adapting sleeves of the body tube, the eyepiece and the objective. Finding the tubes that are suitable for these lenses may be the most challenging part of this project. Look for these tubes in plastic goods and in hardware stores. Finding odd parts is often the hardest task for the amateur scientist, but it can also be a challenging process leading to creative solutions.

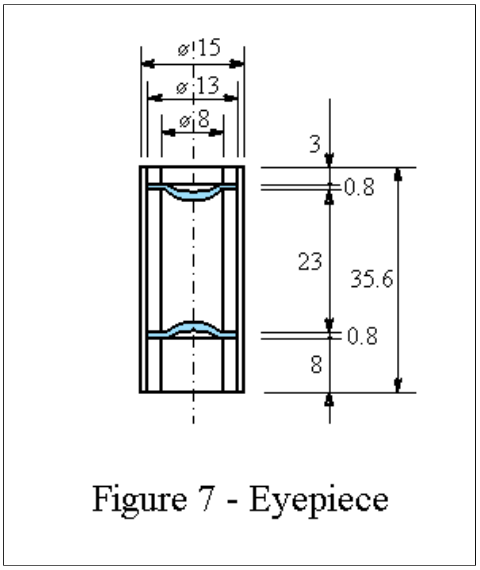

Figure 7 - Eyepiece

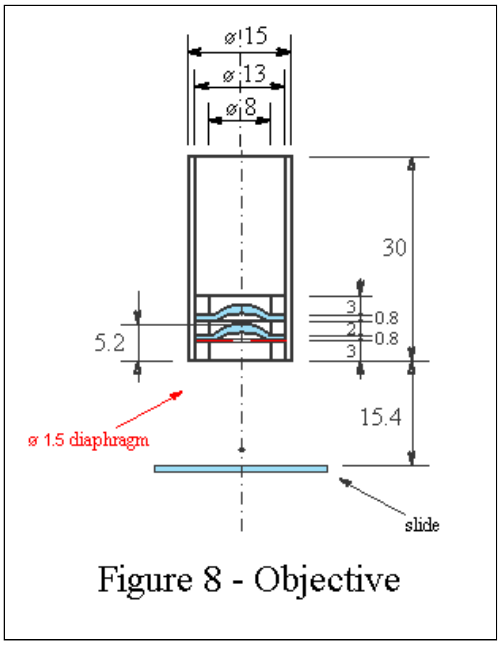

Figure 8 - Objective

OBJECTIVE

In commercial quality objectives, plano-convex lenses and special menisci are often used. Several of these menisci are mounted close to one another with the plane or concave surface facing the specimen. For our objective lens system, place the two remaining menisci at about 2 mm from each other by means of a little gap ring (see Figure 8). As mentioned previously, it is preferable to make the objective tube of plastic rather than cardboard.

If you use only one of these lenses in the objective, you will obtain a magnification that is about one half of the one described here. You can use this idea to make objectives that have different magnification.

DIAPHRAGM OF THE OBJECTIVE

When I first tested the microscope described above, I saw almost nothing. The image was extremely blurred and difficult to focus. The reason for this is that the lenses obtained from the disposable cameras are afflicted by strong aberrations when they are used at their full opening. Fortunately, it is possible to improve the image by 'stopping-down' the size of the objective lens so that the light is allowed to pass through only the central portion of the lens. To do this I place a diaphragm (containing a small hole) in front of the objective lens.

Using a piece of dark plastic film scavenged form an old floppy disk, I made a diaphragm with a 1.5 mm diameter aperture and placed it in front of the first lens of the objective. The results were very satisfactory. In fact, I were able to distinguish the small suction cups on the antennas (feelers) of aphids, and I could observe protists.

The aperture of the diaphragm depends on the lenses you are using, the power of the objective, its level of correction, etc. Keep in mind that, as the diameter of the diaphragm decreases, the quantity of light passing through the objective will also decrease. You will, therefore, have to use more light to see the image adequately. On the other hand you should not make this aperture too large because the sharpness of the image will start to decrease. Try different diaphragm diameters until you obtain a suitably sharp image.

Using glass lenses improves the quality of the image, but not radically. In fact, to obtain sharper images one needs to use achromatic lenses.

INSTALLING THE OPTICS

The objective and the eyepiece must be mounted in the body tube. Figure 9 shows the main optical dimensions of the microscope and the physical dimensions of these components. If you choose to make the eyepiece or the objective using different lenses that those I describe, the dimensions I provide here will no longer apply. Feel free to modify this project according to the materials that are available to you. Use the information in this article as a starting point.

Low-contrast in your images may be caused by reflections from the inner walls of the microscope. To eliminate this problem, line the inside of the body tube with a tube made from black cardboard, or – better still – from black velvet. If you use cardboard, you may find that you are still bothered by reflections. As a further preventive measure you can install an antireflection diaphragm in the tube. (See Figure 9.) It should have an aperture of about 10 mm in diameter (for this model). Removing the reflexes will strongly increase the contrast of the images.

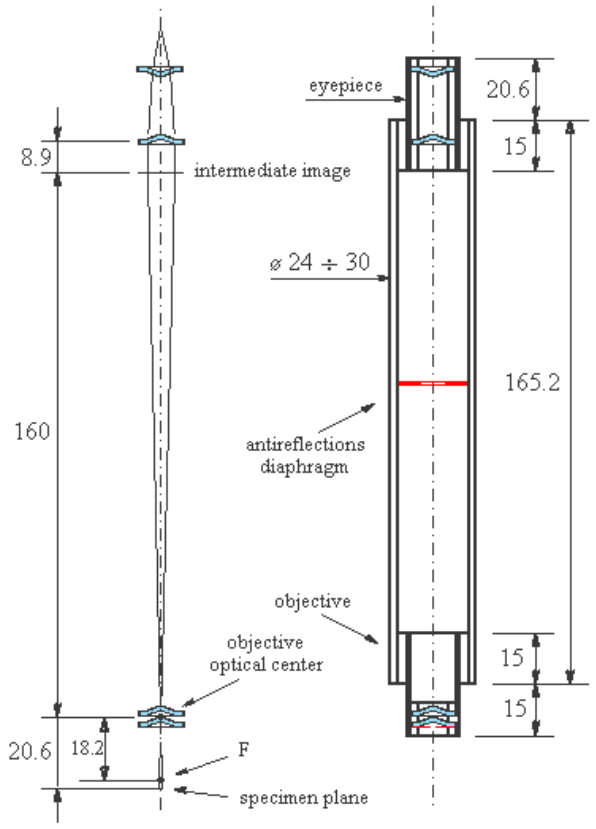

Figure 9 - Optical scheme of the microscope.

MICROSCOPE MAGNIFICATION

What is the magnification of this microscope ?
You can calculate the magnification of your microscope by means of the optical formulas in Table 1. As indicated by formula 6, the magnification of a microscope (Mmic) is given by the product of the power of the objective (Mob) and that of the eyepiece (Mep):

Mmic = Mob × Mep

To use this relationship, we need to calculate the magnification power of the objective and of the eyepiece.

MAGNIFICATION POWER OF THE OBJECTIVE
Applying formula 2 of Table 1 to the objective that we built, and using fa = fb = 35 mm and d = 2.8 mm, we calculate the focal length of the objective:
fob = 18.2 mm
Applying formula 1 of Table 1, and using an image distance q = 160 mm (See Figure 9), we determine that the distance objective-specimen is:
p = 20.6 mm
Applying formula 5 of Table 1, and using the above values for p and q, the power of the objective is:
Mob = 160/20.6
Mob = 7.77

MAGNIFICATION POWER OF THE EYEPIECE
Applying formula 2 of Table 1 to the eyepiece that we built, and using fa = fb = 35 mm and d = 23 mm, we determine that:
fep = 26,06 mm.
And by applying the formula 4 of Table 1, we calculate that:
Mep = 250/26.06 = 9.6

TOTAL MAGNIFICATION OF THE MICROSCOPE
Applying formula 6 of Table 1, the magnification of the microscope is:
Mmic = 7.77 × 9.6
Mmic = 74.6

There is also an experimental way of determining the power of a microscope. Take a ruler with thin and sharp divisions and place it under the objective and focus its image. Place a second ruler at the distance of 250 mm from your eyes. Now, look through the microscope with one eye and focus your other eye on the second ruler. Superimpose the two images and determine how many divisions of the first ruler seen with the microscope correspond to the second ruler seen with naked eye. The first time you try this exercise you may find the comparison rather difficult. Do not get discouraged. With a little practice and perseverance you should succeed. For an amateur

microscopist, optical acrobatics of this type are quite normal. Moreover, despite your best efforts to make careful calculations, measurement errors are unavoidable. That is why it is a good idea to double check your calculations with an empirical method. Moreover, I suspect that many people enjoy this kind of challenge.

FOCUSING

To obtain sharp images, you have to adjust the distance between the objective and the specimen. This operation is referred to as : "focusing". In more expensive microscopes, this adjustment is made by means of mechanisms that are rather complex to build. Our microscope is focused by a simple – yet effective – mechanism. The body tube is held in place by friction. It will not slip downward on its own, but it will slide up and down in response to a little force.

As illustrated in Figure 3, the body tube is placed into two yokes. With some screws it is possible adjust the clamping force with which the body tube is kept in place. Adjust these screws so that the body tube is tight enough to prevent it from falling downward under its own weight, but loose enough to allow it to be moved up or down by hand.

USE OF THE INSTRUMENT

Get a lamp with a frosted bulb and draw it near the microscope. Switch it on and adjust the mirror until the field is brightly and uniformly illuminated. Place a specimen on a microscope slide, add a few drops of water and cover the specimen with a coverslip. Centre the specimen on the stage under the objective. Adjust the focus. If necessary, replace the diaphragm with another in order to obtain a good contrast of the image. Once everything is working well, adjust the position of the slide to explore the different parts of the specimen. Never use direct sunlight - the images would be too bright and would lack contrast, and you would not see any detail.

2nd PART: IMPROVEMENTS

The microscope described above is inexpensive and fairly easy to build. However, there are many improvements that you can make. In particular, you can use more sophisticated lenses and better focusing mechanisms. Although these modifications will make the microscope more complex to build and operate, I feel that many readers will enjoy the challenge. Those who experiment with modifications will definitely learn from their efforts. In the following section I provide you with information that I hope will guide you with your improvements.

The best way to improve the performance of this microscope is by using better lenses. The first (and easiest) thing to do is replace your plastic lenses with glass lenses. Something as simple as this will give you a substantial improvement.

One of the main problem with any lens is ‘chromatic aberration’ which has to do with the inability of a lens to focus light of differing wavelengths to the same point. This is a greater problem for objective lenses than it is for eyepieces, and it is discussed in greater detail under the ‘Objectives’ heading. Fortunately, It is not necessary to use special achromatic lenses for eyepieces. It is possible to remove much of the chromatic aberration from eyepieces through the proper positioning of two plano-convex lenses. Let us start our ‘improvements’, then, with the study of amateur eyepiece construction.

EYEPIECES

The eyepiece has the task of magnifying the image formed by the objective, and in doing so it should introduce as little optical aberration as possible. There are many eyepiece models, but here I will describe only those that are the easiest to build. You can make a high quality eyepiece with only two plano-convex lenses.

Two particularly simple eyepieces are the Ramsden and the Huygens type. Both were designed by their inventors to minimize optical aberrations. In some cases they are designed to compensate for aberrations produced by the objectives. These models are widely used in modern microscopes and in telescopes. The Huygens eyepiece is probably the most widespread model in use today. If you manage to obtain achromatic doublets of short focal length lenses you can build three other models of eyepieces of still higher quality.

Note that a field diaphragm is often inserted in the focal plane of the eyepiece. This diaphragm has the important function of preventing reflections from the inner surfaces of the eyepiece.

Ramsden eyepiece.
The Ramsden eyepiece is made with two plano-convex lenses of same focal length (fa = fb), with the convex surfaces facing each other (Figure 10). The lens nearest the observer is referred to as the eye lens while the other is called the field lens. For best reduction of chromatic aberration the distance ‘d’ between these lenses should be equal to their focal length. Unfortunately, this separation introduces several problems, one of which is that the eye lens will focus on any imperfections and dust particles on the field lens. To reduce this effect the distance between the lenses is reduced to approximately two third of its focal length: d = 2/3fa. Unfortunately, this does not eliminate the problem completely. You could also try placing the two lenses one half of the focal length apart: d = fa/2. Another problem with this lens is that it has quite a narrow field of view.

Huygens eyepiece.
This eyepiece is made with two plano-convex or biconvex lenses. Both lenses are oriented with the convex surface toward the objective. (See Figure 10). These lenses must be of different focal lengths. In general, the two focal lengths have to be in the ratio somewhere between 1:3 and 1:2. The distance between the lenses must be equal to half of the sum of the respective focal lengths: d = (fa+fb)/2, where fa is the field lens focal length and fb is the eye lens focal length. This is just the average of the two focal lengths. Let's consider a couple of examples. If fa = 30 mm and fb = 10 mm, the separation of the two plane surfaces should be 20 mm. In another example, fa =

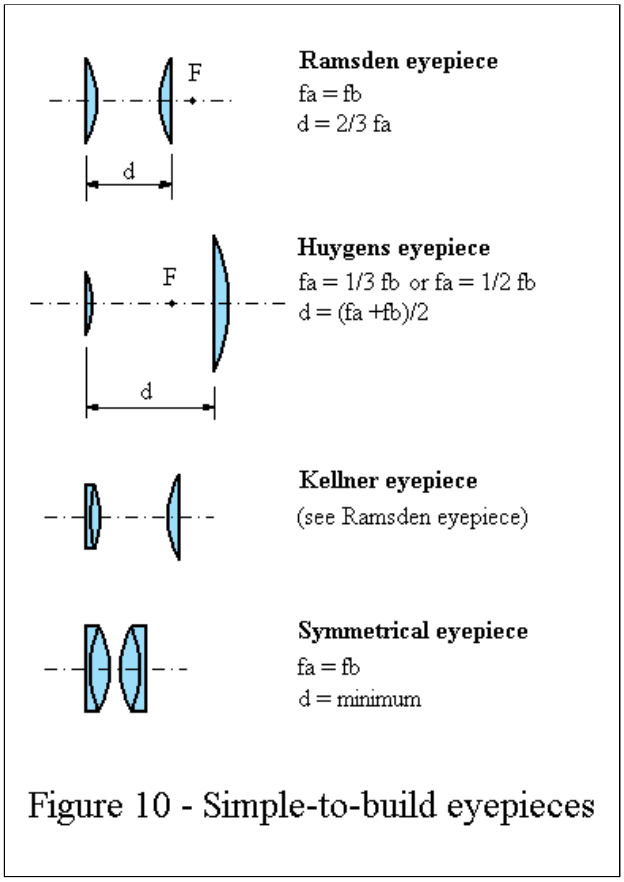

Figure 10 - Simple-to-build eyepieces

30 mm and fb = 15 mm. The separation between the two plane surfaces should be 22.5 mm. The focal plane of the Huygens eyepiece is located between the two lenses. Hence, the field diaphragm has to be on the focal plane of the eye lens.

Kellner eyepiece.
This model is derived from the Ramsden eyepiece. It is made by replacing the eye lens of the Ramsden with an achromatic doublet. With this eyepiece model you should obtain better chromatic correction and a greater eye relief. (Eye relief is the distance of the eye behind the eyepiece).

Similarly, you can modify the Huygens eyepiece with an achromatic eye lens, and, in this case you could use a biconvex lens for the field lens. In these eyepieces, the inter-lens spacing is derived from the focal lengths in the same way as we did for the lenses from which they are derived.

Symmetrical eyepiece.
This model, which is very simple to build, is made with two identical achromatic doublets that face each other in mirror symmetry. Hence the name. (See Figure 10.) They must be kept very close together. The focal length of this eyepiece is equal to about one half of that of each doublet. Its excellent performance includes good correction of aberrations, a very wide field of view and a high eye relief. Often, this model is called a Plössl eyepiece, but this is incorrect because the Plössl eyepiece has another lens placed in an intermediate position. It is more accurate to call this model a *symmetrical*eyepiece.

OBJECTIVES

I recall that the objective has the role of producing a magnified image of the object you are observing. (This image, of course, is further magnified by the eyepiece.) Unlike the eyepiece, which can be at least partially corrected for chromatic aberration without using achromatic lenses, the objectives can not. They must be made with achromatic lenses in order to produce sharp images.

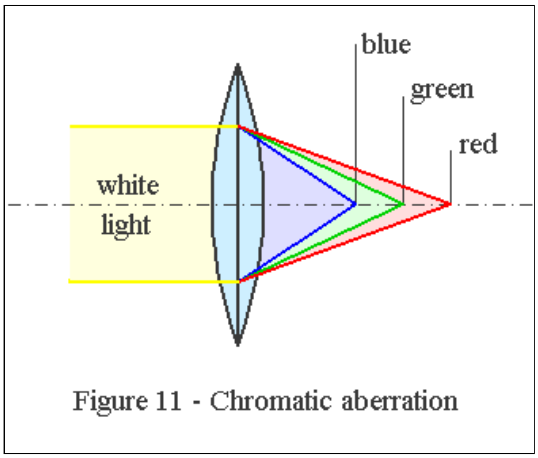

Figure 11 - Chromatic aberration

I digress for a moment to discuss chromatic aberration in a little more detail.

Just like a prism, a lens will bend light to a varying degree depending on the color of the light. Because of this phenomenon, a normal lens will focus the various colors at different locations (as shown in Figure 11), thus producing a blurred image. This phenomenon is called **chromatic aberration** and it is the worst of several aberrations that can afflict normal lenses. The first microscopists had a lot of trouble with this problem, and for a long time early microscopes, like early telescopes, produced blurred images. This problem was resolved when they started using objectives made of two lenses with different indices of refraction. These objectives are designed in such a way that the chromatic defect produced by the first lens is compensated by the opposite defect produced by the second lens. This has the result that the various colors (or wavelengths) are focused at (almost) the same location - thereby producing a sharper image.

Usually, these lenses are cemented together in pairs (doublets) and the red and blue colors of the image are made to coincide. (The other colors may not coincide perfectly.) These are known as *achromatic lenses*. Sometimes they are cemented together in groups of three (triplets) to obtain a chromatic coincidence of three colors - usually red, green and blue. These lenses are called *apochromatic*, and they are substantially better than the achromatic lenses. In other cases the individual lenses are kept separate.

Objectives are also afflicted by other aberrations, among them being the spherical aberrations which are probably the worst form of aberration after the chromatic aberrations. The *planachromatic* objectives yield a flat image and are designed for photography. The type of chromatic correction used in these objectives is intermediate between the achromatic and the apochromatic objectives.

With normal lenses (non achromatic) you can obtain fairly good images as long as you limit yourself to moderate magnifications. To obtain high magnifications, you absolutely require achromatic lenses. For this project, we can use either achromatic or non-achromatic lenses. The use of normal lenses demonstrates the effect of chromatic aberration and the importance of eliminating it as the magnification is increased. In general, the use of normal lenses allows you to obtain satisfactory images up to about 100 X, providing you use a diaphragm in front of the objective.

The objective is the most important part of the microscope. The manufacturers of commercial microscopes design their objectives by means of complex optical calculations and produce lenses according to parameters that they have defined analytically. Both the design and the manufacture of objectives are beyond the range of the amateur. However, even though the fabrication of objectives is more complex than that of eyepieces, we will try to make a better objective than the one we used in the first section. We will try to obtain the best possible performance with normal lenses. Any further improvement will require the use of achromatic lenses.

Again, glass lenses are usually of higher quality than plastic lenses. So, as a first step, if you have short-focal-length plano-convex glass lenses, use them rather than the plastic lenses.

If you have a binoculars eyepiece, use it as a condenser. Orient it with the eye lens upwards.

Figure 12
Mechanical length
of the body tube.

In manufactured objectives, the first lens (the one closest to the specimen) is often made of a little plano-convex lens. It is followed by one or more other lenses. They can be plano-convex, meniscus or achromatic lenses. Normally, the lenses are placed with the plane or concave surface toward the specimen. When two equal achromatic doublets are used, they are often placed in a symmetrical arrangement. Other types of objectives follow schemes that are similar to these, and the correction of chromatic aberrations is not always made with cemented lenses. Often, low power objectives are made of a single achromatic doublet.

For the amateur microscope builder, the construction of objectives should follow these principles :
- Do not try to obtain high magnification.
- Use as few lenses as possible.
- Use plano-convex lenses or menisci or achromatic doublets.
- Place the most powerful lens closest to the specimen. (If possible use a plano-convex lens).
- Keep the plane or concave surfaces turned toward the specimen.
- Try to keep all of the lenses centered.
- Stop-down the objective with a diaphragm to reduce the aberrations.
- If possible, use an achromatic doublet alone.
- If you use two identical achromatic doublets, place them facing each other in mirror symmetry, and try to keep them at different distances.
- Try to use a plano-convex lens followed by an achromatic doublet, or two equal doublets.

The use of achromatic lenses will lead to high quality images without the need of stopping-down the objective. Buying a 10X or 20X achromatic objective will eliminate many problems. If you use a commercial objective specifically designed for a microscope, the mechanical tube length **L** (normally 160 or 170 mm) should be written on it. As shown in Figure 12, this is the distance between the stop of the objective and that of the eyepiece. Clearly, if you use an achromatic objective for your microscope, you should use a good quality eyepiece also, such as a 10X Huygens eyepiece.

On the market there are also *infinity-corrected objectives*. In this case, the mechanical tube length is indicated by the symbol for infinity. These objectives are designed for the specimen to be at the exact focal point of the objective. This results in the image being produced at infinity. An intermediate lens must be placed in the body tube to focus this image on the focal plane of the eyepiece. Because of the need for this intermediate lens, the use of the infinity-corrected objectives is a little more complicated than the normal ones. For the sake of simplicity it is better to avoid this type of objective. If you want more information on these objectives, please refer to the web site that I have indicated in the bibliography.

OPTICAL CALCULATIONS

The following expressions will help you to calculate the focal length and the power of simple eyepieces and objectives, assuming they are systems of thin lenses. All dimensions are expressed in mm. To determine the focal length of these lenses read our article: "From Lenses to Optical Instruments".

Table 1 - Some optical formulas

Terminology	f	focal length of a single lens or system of lenses
	p	objective-object distance
	q	objective-image distance
	f_a	focal length of the lens A (e.g: the field lens)
	f_b	focal length of the lens B (e.g: the eye lens)
	f_{ab}	focal length of the system of two lenses A and B
	d	distance between two thin lenses
	D	distance of the focus plane from the front lens

1	relationship between the focal length and the p and q distances	$1/f = 1/p + 1/q$
2	focal length of a system of two lenses (e.g: the eyepiece)	$f_{ab} = f_a f_b/(f_a+f_b-d)$
3	distance of the front focal plane from the nearer lens	$D = f_{ab}(f_b-d)/f_b$
4	eyepiece magnification power	$M_{ep} = 250/f_{ab}$
5	objective magnification power	$M_{ob} = q/p$

6	magnification power of the microscope	$M_{mic} = M_{ob} \times M_{ep}$

COARSE FOCUSING SYSTEM

The microscope described in the first part of this article is focused simply by pushing the body tube up and down by hand. This, unfortunately, does not exhibit the fine control that we would like. However, with a little effort you can add a steel wire mechanism that will give better control over the motion of the tube. As you turn a knob, the steel wire will gently, but firmly, pull the body tube up or down. (See Figure 13.) This improvement will cost you little more than another dollar or two.

Figure 13 - Steel cable focusing system

Materials for the focusing device:
- Steel cable for model aircraft construction (0.4 mm-diameter nylon-coated flexible steel braided cable. The outside diameter of this cable should be 0.7 mm). You can buy this cable in a model aircraft or hardware store.
- Steel shaft ø 10 mm (its surface has to be regular and smooth)
- Two knobs
- two flat tip M 4 x 5 set bolts for the knobs
- 10 x 20 x 70 mm rigid plastic to make the two bearings for the shaft
- two cylindrical head tapping screws ø 3.5 x 35 mm for the bearings
- A tube to obtain the spacers
- An aluminum block 8 x 10 x 25 mm to make the two ends for the cable
- Two M 3 x 7 mm bolts and nuts to hold the lug support to the tube
- Two flat tip M 3 x 5 set bolts to stop the cable.

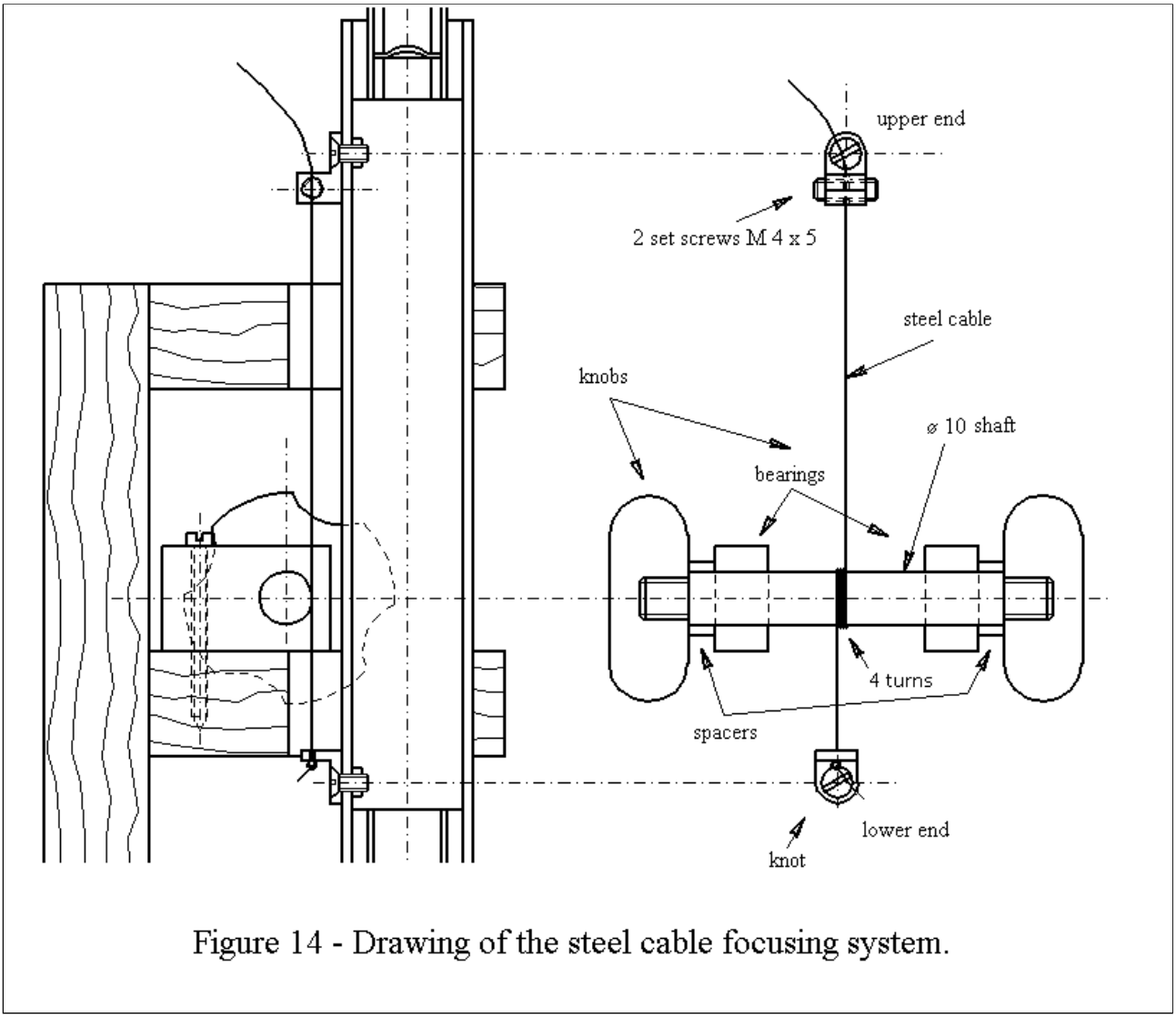

Figure 14 - Drawing of the steel cable focusing system.

The heart of this focusing device is a thin and flexible steel cable that is fixed to both top and bottom of the body tube (see Figure 14). The cable is pulled by a rotatable shaft that passes through bearings fixed to one of the tube's supports. The bearings for this shaft could be plastic blocks screwed to the support, but you may have other ideas. By referring to the figure 13, the holes for the screws have to be 0.5 mm larger than the screws to allow the bearings to align with the shaft. On the contrary, the holes for the shaft have to be exact while allowing a fluent movement.

Before mounting this system, deepen the notches of the wooden supports in order to allow the passage of the ends and their attached hardware. Slip the shaft onto the plastic bearings and screw them to the wooden supports. Make sure that the cable is parallel to the body tube. Drill the knobs to the same diameter of the shaft. With a file, make a little flat surface on the shaft. Mount a bolt on each knob and mount them on the shaft.

You may want to clamp the plastic bearings to the wooden support temporarily before you install the shaft and the cable. Once the shaft and cable are in place, the plastic bearings can be shifted so that the cable lines up with the tube. When you are happy with the lay-out, screw the plastic bearings to the wooden support.

The cable must be quite flexible because it has to be wrapped four times around the shaft to develop enough friction. Figure 14 shows how the cable ends are attached to the body tube. Two ends (in aluminum or steel) are bolted to the body tube. Cut a piece of 330 mm from the steel cable. Made a knot in the bottom part and made the cable pass through the hole in the lower end. Wrap the cable for four turns around the shaft. Now, made the cable pass through the upper end. Arrange the turns side by side, then, with a pincer clamp the end of the cable and pull with a force of 2 Kg about wile moving forwards and backward the knobs. Stop the cable with the upper bolts against each other. Repeat the operation some times, until the cable is enough tightened. The main tube has to move easily but firmly. Make sure that the cable does not slip on the shaft when the shaft is turned. If it does, repeat the tension of the cable.

Now, the role of brake (that prevent to the main tube to fall) are performed by the bearings of the shaft. So, you can relax the wooden "V" supports. If necessary, make a saw cutting on each bearing so that by tightening the screw, the braking force increases.

Despite its odd appearance, this focusing system works very well. Its movement is more fluid than the much more complicated (and expensive) mechanism that uses a dovetail slide and a rack and pinion.

FINE FOCUSING SYSTEM

High quality microscopes are usually equipped with both coarse-focus and fine-focus adjustments. The coarse adjustment provides a quick but rough focus, while the fine-focus allows you to make a more precise adjustment. To equip our little microscope with a fine focusing adjustment, we will use a mechanism that lifts the stage by a fraction of a millimeter. Since the stage is screwed solidly to the microscope body we can't expect to move it very much. The mechanism I have chosen to lift the stage is simple but effective. As shown in Figure 15, it is a differential screw made up of two coaxial bolts of different pitch. When the differential screw is rotated counterclockwise, the larger bolt will come out of its nut a greater distance than the smaller bolt goes in. The stage will be pushed upwards by a distance equal to the difference of the pitch of the two bolts.

To make this fine focusing mechanism, you can use a M 3 and a M 5 bolts. Because the thread of one bolt has a pitch of 0.8 mm while the thread of the second has a pitch of 0.5 mm, a complete rotation of the differential screw will lift the stage only of 0.3 mm.

First, cut away their heads then join them end-to-end. To join the two bolts, with a lathe drill and thread one end of the M 5 bolt, screw and tighten the two bolts together in a coaxial way. With washers and nuts, fix a cap from a tube of toothpaste on the middle portion of the differential screw. The differential screw has to be 10 mm about longer than the distance between the base and the stage. Drill two aligned holes, one under the stage and the other on the base of the microscope. With a vise, press the two nuts into these holes.

In order to mount the differential screw, relax the bolt that fix the stage, then screw the differential screw in the M 5 nut for about 11 mm. Tighten again the bolts of the stage, then screw the differential screw into the M 3 nut. You should attain a position where the differential screw turns freely. Always keep the differential screw in this position, except for when you use this focusing device.

You should not rotate the differential screw for more than one turn. Before you use the fine adjustment, make sure that you get the best focus you can with the coarse adjustment, then sharpen up the image with the fine adjustment.

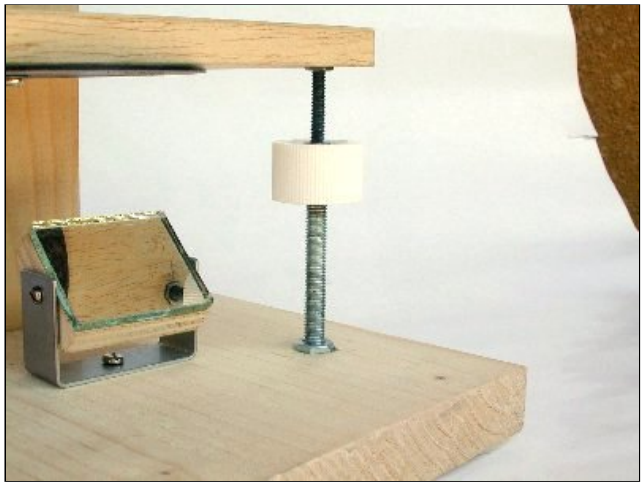

Figure 15 - Fine focusing device made using a differential screw.

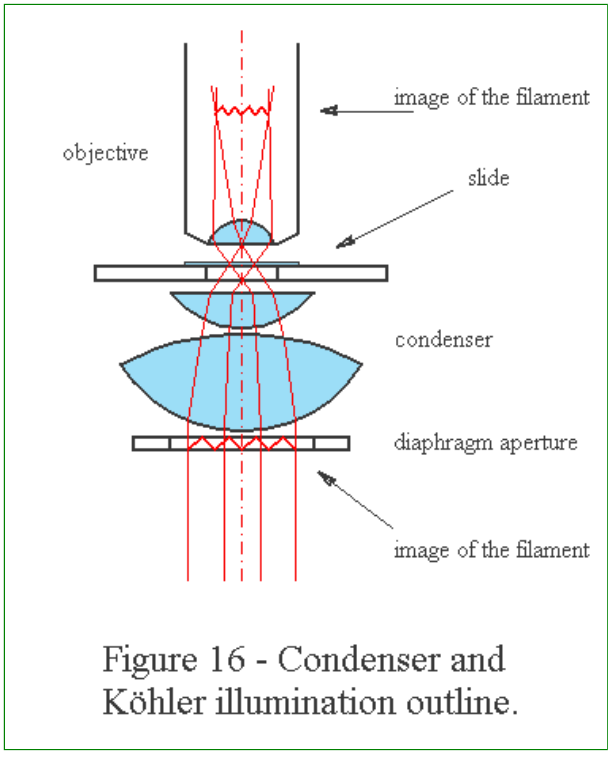

Figure 16 - Condenser and Köhler illumination outline.

CONDENSER

The role of the condenser is to concentrate the light on the specimen. This is particularly important at high magnifications where more intense light is required. For example, a magnification of 100 requires four times as much light as a magnification of 50 – if you want to maintain the image brightness.

Converging lens and rotating diaphragm
For this simple microscope, a condenser is not indispensable, but if you exceed the 100 magnifications it become necessary. A simple condenser is a strong plano-convex lens installed under the hole in the stage. This lens should have a focal length of about 25 mm, and it must have the plane surface turned upward. If you can obtain better optical components, you could add a second powerful biconvex lens under the first one as illustrated in figure 16. It is also possible to use an eyepieces as condenser. With a few money, it is possible to buy in the stalls (booths?) good quality binoculars.

Commercial microscope condensers are usually provided with an iris diaphragm, where the aperture is continuously variable. An iris diaphragm is rather expensive for this simple microscope, and making one would be a rather laborious undertaking. Besides, the rotating diaphragm described above will work well even though it is not very sophisticated. If you do obtain an iris diaphragm, place it under the condenser.

Adjusting the condenser diaphragm
In a commercial microscope with its diaphragm at the maximum aperture, the images are well-resolved, but they are pale and without contrast. As we narrow the aperture, the image will gain contrast, and the outlines will become more pronounced. Moreover, the depth of field will increase. However, as we continue to narrow the aperture, the outline of the objects will fuse and the sharpness of the image will degrade. So, adjust the aperture until you find the best balance between sharpness and contrast of the image.

ILLUMINATING SYSTEM

Mirror and window
Set the microscope close to a window and direct some light on the specimen with the mirror. This is the simplest illuminating system. It is usually used by student microscopes – even those with achromatic objectives, but it is not the best solution.

Mirror and lamp with frosted bulb
If you try to use a fluorescent tube as a light source, you will notice that only the lines running in one direction will be focused; the others will be blurred. This is due to the long and narrow shape of the fluorescent tube. Windows that have irregular shapes can produce a similar effect. What we want are circular and uniformly bright sources of light. Try using a frosted light bulb placed some centimeters from the mirror. This is the best and simplest illuminating condition for this microscope.

Lamp and diffuser
The light sources described above are separate from the microscope. This means that once you are set up you won't be able to move the microscope without altering your lighting conditions. This can be frustrating. We would like to have a light source that moved with the microscope – e.g: one that is part of the microscope body. One way of achieving this is by removing the mirror and replacing it with an illuminator. This can be a closed box containing a lamp. The box has a circular hole in its lid directly below the hole in the stage. The hole of the box must be covered by a diffuser of frosted glass so that the filament of the lamp is not visible. You will need to conduct some tests to determine the best diameter of the hole and the best distance from the microscope. You should also provide this illuminator with diaphragms of different aperture and with a blue filter to raise the color temperature of the filament lamp. With a little effort you can make the intensity of the light adjustable. If you build this illuminator, use a low voltage lamp and materials that are heat-resistant and electrically non-conductive.

Light Emitting Diode (LED)
Today, you can use luminous LED that supply a white and very bright light. These devices produce little heat, have a low energy consumption and are very suitable to build systems of illumination for microscopes. In order to control the brightness of the LED, provide the system by a rheostathttp://www.funsci.com/fun3_en/usph/usph.htm .

Illumination with lamp, lenses and mirror - Köhler illumination
High magnification requires very bright illumination, and there is a technique invented by Köhler – called Köhler illumination – that produces an intense and homogeneous bundle of light. This technique has become standard in modern microscopy. The apparatus is quite complicated, however, and its use is probably not justified for this project. Finally, on the condenser is usually placed a blue filter that increases the color temperature of the filament lamp.

A MICROSCOPE FOR OBSERVING PROTOZOA

If you have arrived this far, it means you are ready to build a little Do-It-Yourself jewel: a microscope whose quality will amaze all those who try it, and in particular those who already have a microscope. Obviously, in order to achieve such a feat, I had to introduce some improvements that will raise the cost of this instrument to about 60 dollars. What characterizes this model is the use of purchased optics. The design of this microscope enables you to observe protozoa, unicellular algae, tissue sections and permanent preparations.

The structure of this microscope is the one you are familiar with and it can be made out of wood, Plexiglas and other materials. It is equipped with coarse focus (steel cable) and fine focus (differential screw). The optics consists of an achromatic 20 or 25 X achromatic objective, a 10 X eyepiece for microscopes and a binocular eyepiece as a condenser.

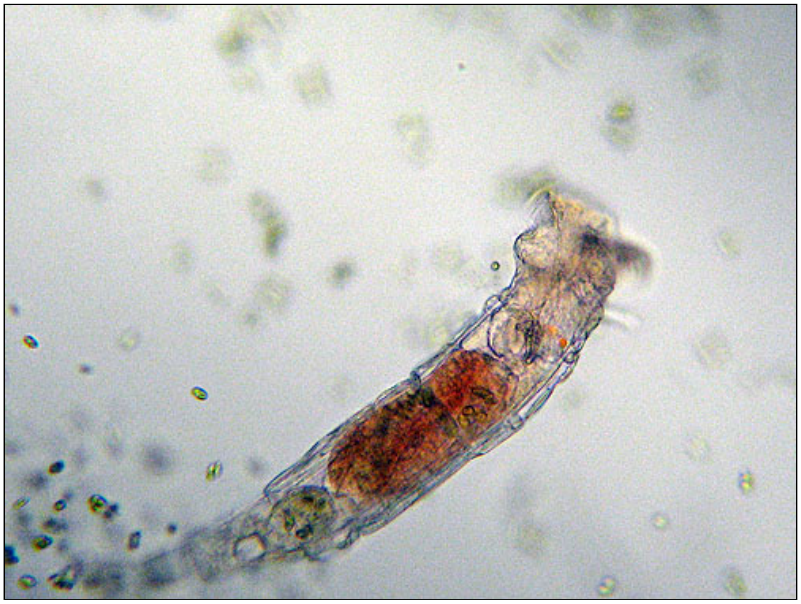

Figure 17 - Microscope for observing protozoa.
The objective and the eyepiece are bought,
The condenser is made with an eyepiece for binoculars.

Figure 18 - Shot of a rotifer taken through the microscope for observing protozoa. Field = approximately 0.6 mm.

Mount the eyepiece "condenser" at the same level as the stage and with the lens of the eye upward. Make a rotating diaphragm with 6 holes of the following diameters: 16, 12, 10, 8, 6 and 4 mm. Mount the rotating diaphragm a few millimetres below the "condenser". In order to follow the incessant movements of the protozoa, purchase a device which allows you to move the microscope slides. This should cost about 20 euro. The coarse focusing, the fine focusing and the adjustable mirror will complete the instrument (figures 17 and 18).

As we said, to obtain well-contrasted images, you must carefully eliminate all internal reflections. To do this, coat the inside of the main tube with black cardboard or black velvet. Fit an internal diaphragm, being careful not to intercept the light directed to the eyepiece. In order to eliminate internal reflections, it can help to use a principal tube of greater size: between 30 and 34 mm in the outside diameter. In this case, you will have to modify the dimensions of the upright and the "V" supports. Also clean the eyepiece and the objective using optical pure cellulose paper or a clean cotton handkerchief. Because of its simplicity, this microscope allows you to get very sharp and contrasted images. This is not always possible with microscopes that have the prism box, which often have internal reflections that are not easily eliminated and over time accumulate dust and patinas on optical surfaces.

The length of the tube of this microscope must be the one indicated on the objective (Figure 12). With an objective of 20 or 25 X and a 10 X Huygens eyepiece, you will obtain a magnification of 200 or 250 X that is perfect for observing protozoa and other microorganisms living in stagnant water. That is the main feature of this microscope and I'm sure you will appreciate the miniature world that this instrument will open up to you.

HOW TO FIND LENSES

I have already told you how you can get the lenses needed to build the first microscope of this article. The optical components for this last microscope can be purchased in:
- surplus market;
- opticians, photography and microscope shops;
- photography, astronomy, minerals and electronics fairs where it is often possible to find lenses and optical instruments, both new and used;
- Internet auctions (e.g. Ebay);
- Mail order retailers of optical products also present on the Internet.

Unlike the situation of a few years ago, the Chinese manufactured eyepieces and objectives are often of high quality, as well as low cost. You can also obtain binocular eyepieces by demolishing old binoculars or those purchased at low cost. If you buy your binoculars, choose those with objectives of 50 mm in diameter, and avoid those of an orange colour. The objectives of these binoculars could be used to build a nice stereoscopic microscope.

OBSERVATIONS

Here, you can find a series of articles that tell you what to observe with a microscope: what to observe with a microscope.

CONCLUSION

Although the little basic instrument described in this article is simple and costs less than about a dollar to build, it will work quite well. Moreover, it will give you an introduction to the principles governing the workings of a professional microscope. Here how with little things you can understand the big ones. If you are inclined to carry this project further, you can experiment with different mechanical improvements, different arrangements of the lenses, higher quality optics, or you can integrate your instrument with devices that can improve its performance. Treat this project as 'open-ended'. I hope that this little project will stimulate your curiosity and your creativity.

BIBLIOGRAPHY

Would you like to know more about microscopes? Here are some resources available on the internet: The first site, The Molecular Expressions Website, is a goldmine of information about microscopy.

http://microscopy.fsu.edu/primer/anatomy/anatomy.html Anatomy of the microscope
http://microscopy.fsu.edu/index.html Optics, microscopy, images at the microscope
http://micro.magnet.fsu.edu/optics/ Optics and science
http://en.wikipedia.org/wiki/Eyepiece For more on eyepieces. Wikipedia has many other topics on optics. In particular, look up 'lens (optics)'. It has a nice discussion of aberrations.
http://micro.magnet.fsu.edu/moviegallery/pondscum.html Pictures and movies of organisms that live in ponds.