# DOCUMENT RESUME

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ABSTRACT

Instructions accompanied by illustrations for building a low-cost demonstration spectroscope are presented. Materials and tools are pictured and labeled. Cost is estimated at five dollars (in 1980) and twelve hours of work are required to build the spectroscope. (SA)

# how to build a low-cost spectroscope

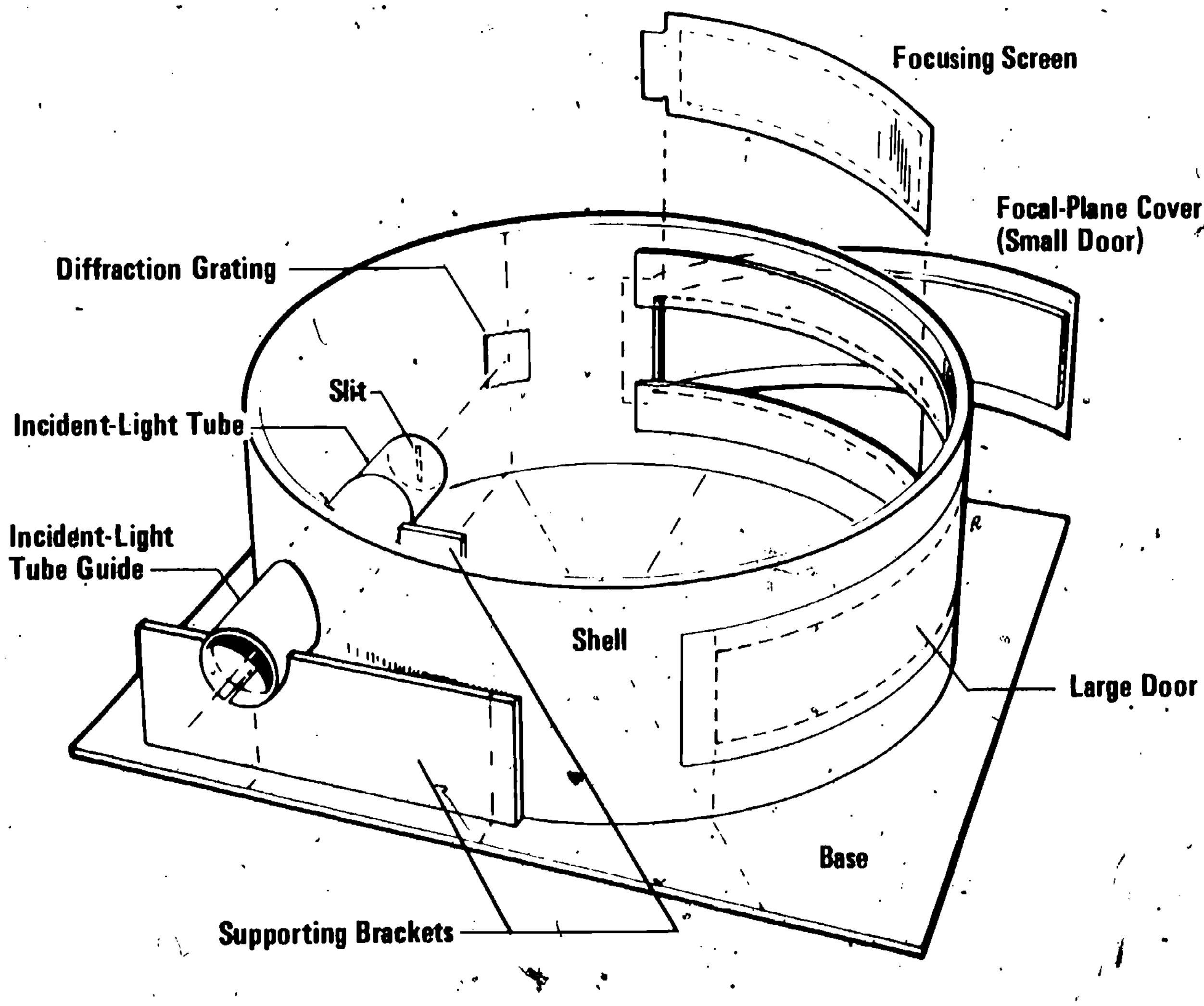
This leaflet is for review and tryout at Teacher Workshops. Comments and criticisms should be forwarded to Mr. K. S. [illegible], Special Action [illegible] FE, National Aeronautics and Space Administration, Washington, D.C. 20546.

# INTRODUCTION

In 1973 the National Aeronautics and Space Administration published a series of books called "Skylab Experiments." The first volume in the series contained some guidelines for constructing a reflection grating spectroscope. Requests for more information have been received from several educational sources. This booklet was prepared in response to these requests as part of the on-going educational activities of the National Aeronautics and Space Administration.

The booklet shows how a demonstration spectroscope can be made for a total cost of around $5 and about 12 hours of work. Instead of the more familiar prisms or transmission gratings, the instrument uses a reflection diffraction grating to disperse the spectrum for observation. The reflection grating is more often used in spectral analysis because of its greater spectral dispersion properties over a wider wavelength range than either of the other devices.

Included is an appendix that explains the theory behind the principles of dispersion of a spectrum by refraction and diffraction. Descriptions of some of the more advanced spectroscopes used in NASA's Skylab Program show that the instrument built by following the instructions in this booklet is fundamentally the same type of device.



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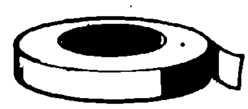
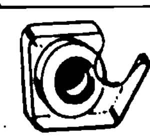
# MATERIALS

| | Suggested Source |
|---|---|
| **HEAVYWEIGHT MOUNTING BOARD**<br>*Crescent Brand 3X Process Board or equivalent 76.2 x 101.6 cm (sold as 30x40 in.)* | *Artists' supply store* |
| **CONCRETE-COLUMN FORM TUBE**<br>*40.6-cm (16-in.) inside diameter* | *Concrete construction material supplier or concrete contractor. Get the shortest length available. You only need 15.24 cm (6 in.).* |
| **CARDBOARD TUBE**<br>*Approximately 5 cm (2 in.) in diameter, 40 cm (15.75 in.) long* | *Core from roll of aluminum foil or gift-wrapping paper* |
| **WHITE GLUE, small bottle**<br>*0.236 liter (8 oz)* | *Any hardware or drug store* |
| **WAXED PAPER** *18x25 cm (7x10 in.)* | *Any grocery store* |
| **MASKING TAPE, small roll**<br>*2.54 cm (1 in.) in width*  | *Any hardware or paint store* |
| **LIGHTWEIGHT ART BOARD**<br>*3-ply Bristol or equivalent, at least 61 cm square (24 in. square)* | *Artists' supply store* |
| **DOUBLE-EDGED RAZOR BLADE** | *Any grocery or drug store* |
| **FILE CARD** *7.6 x 12.7 cm (3x5 in.)* | *Any grocery or drug store* |
| **MENDING TAPE** *19 mm (3/4 in.) wide*<br>*Scotch brand Magic Mending, 3M No. 810 or equivalent*  | *Any grocery or drug store* |
| **FLAT BLACK PAINT** *latex or oil* | *Any hardware or paint store* |
| **DRAFTING MYLAR** *6x19 cm (2-3/8 x 7½ in.)* | *Artist's or draftsman's supply store* |
| **SMALL HAND MIRROR** | *Any drug store* |
| **DIFFRACTION GRATING**<br>*21.6 x 28 cm (8½x11 in.), 13,400 lines per inch* | *Available from sources such as:*<br>*Edmund Scientific Company*<br>*Edscorp Building*<br>*Barrington, NJ 08007 (Part No. 50,201)* |

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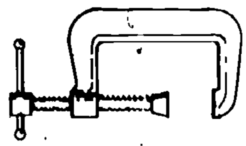
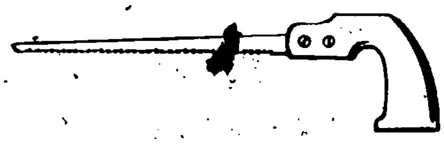
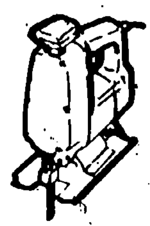
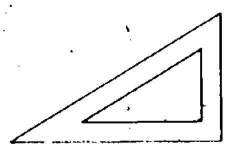
# TOOLS

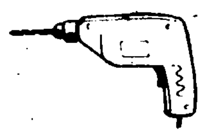
**METRIC SCALE** 

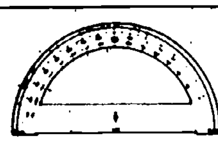
**SHARP PENCIL — 2H hardness** 

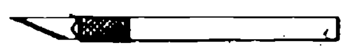
**SMALL C-CLAMPS (4)** 

**KEYHOLE SAW**  **or saber saw** 

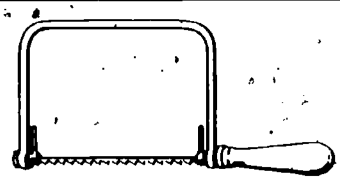
**TRIANGLE – 30–60°** 

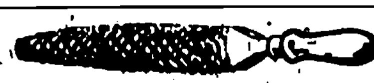
**DRILL – manual or power, with 5/16" bit**  

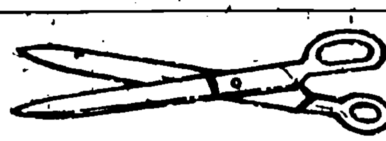
**PROTRACTOR** 

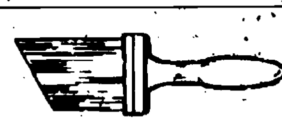
**SHARP KNIFE – like X-acto with No. 11 blade** 

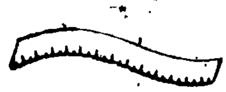
**or utility knife** 

**COPING SAW** 

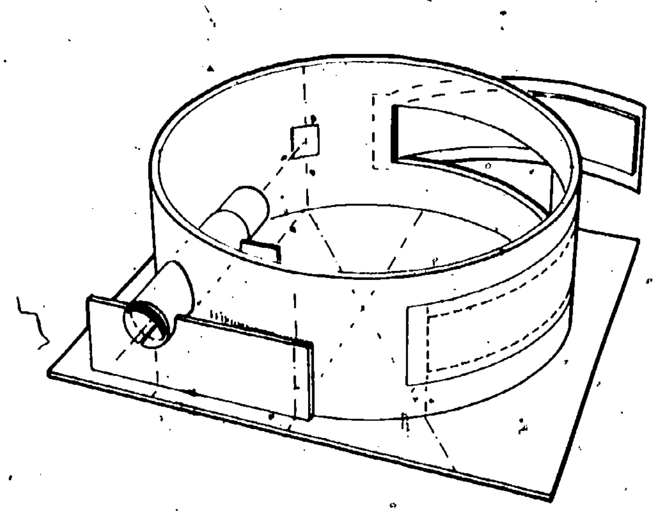
**CONVEX WOOD RASP** 

**HEAVY DUTY SCISSORS** 

**PAINT BRUSH**  **diagonal cut bristle shape preferred for tight corners** 

**FLEXIBLE STRAIGHTEDGE approximately 50 cm** 

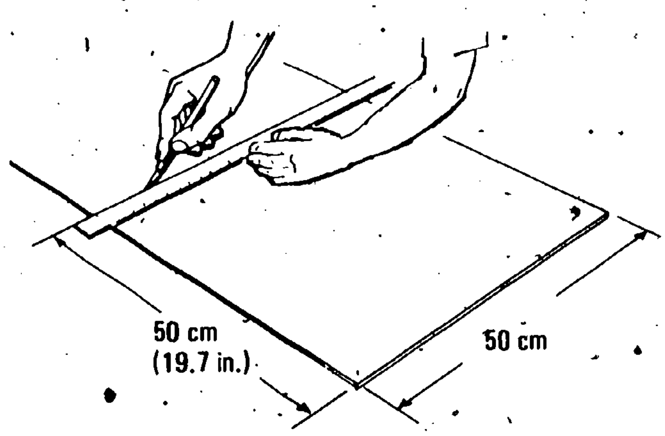
# INSTRUCTIONS



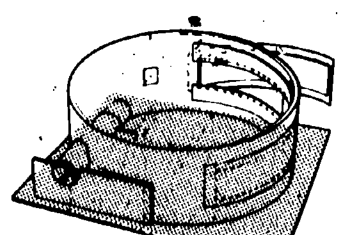
## 1 Cut the base

On the heavyweight mounting board, draw a 50-cm (19.7-in.) square, using two edges of the board for two sides of the square. Cut out the square with an X-acto knife. But be careful. It's easy to slip and cut a few fingers-or the table top on which you are working.

This will be the base of the spectroscope.



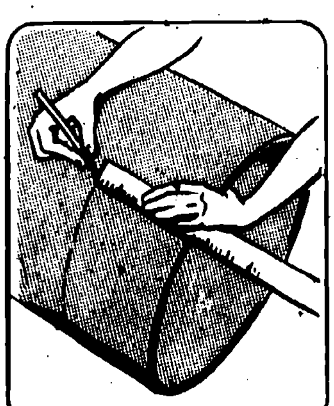

You should use a metal straight edge to guide the cut.



## 2 Prepare the shell

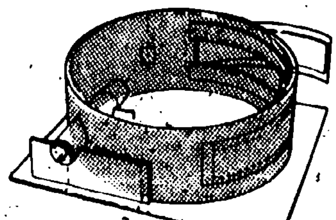
Now cut 15 cm (6 in.) from one end of the concrete column form tube with the key-hole or saber saw. Don't try this alone. You'll need someone to hold the tube steady while you cut. It's also a good idea to clamp the form to a workbench at one end, using one of the C-clamps.

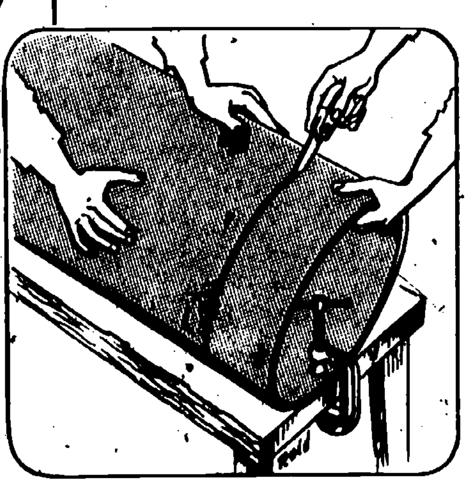
*Note: If the ends of the form tube are uneven or rough, it is advisable to smooth them with medium grade sandpaper before marking the line on which to cut.*



Make a row of dots all around the tube and join with a continuous line.

Let someone help hold the flexible straightedge and the form tube while scribing and sawing.

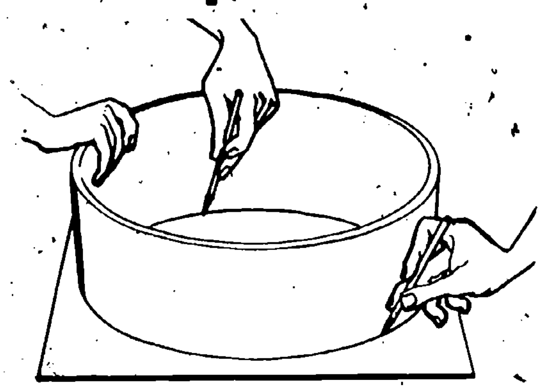


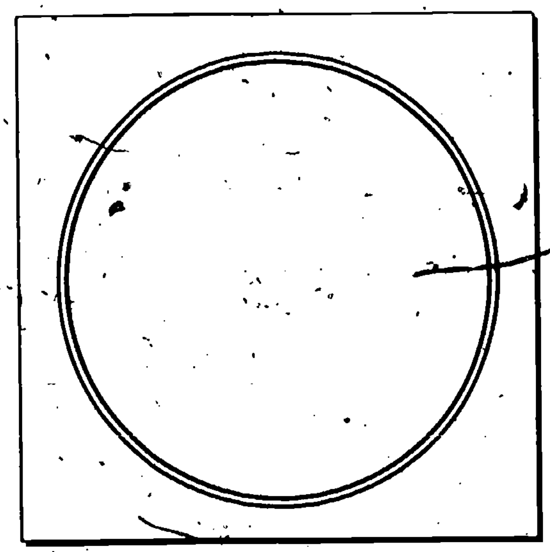


Loosen C-clamp periodically to rotate form tube for proper saw position.

## 3 Establish the shell position

Now set the shell on the base, as nearly centered as possible, with the edge of the shell you cut facing up. Hold the shell steady and carefully draw its outline on the base, inside as well as outside.



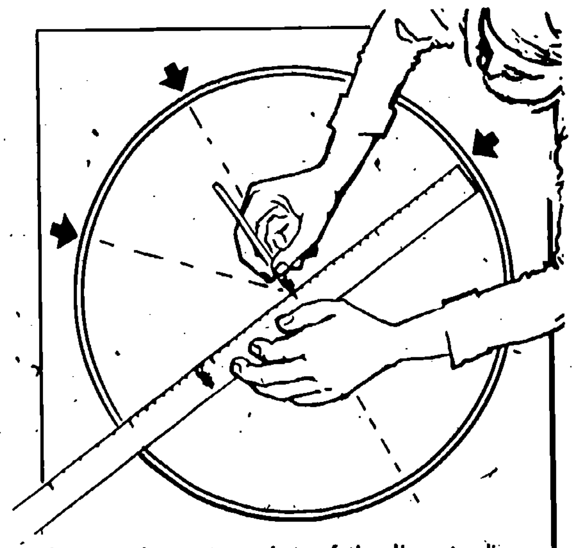


## 4 Plot the plan

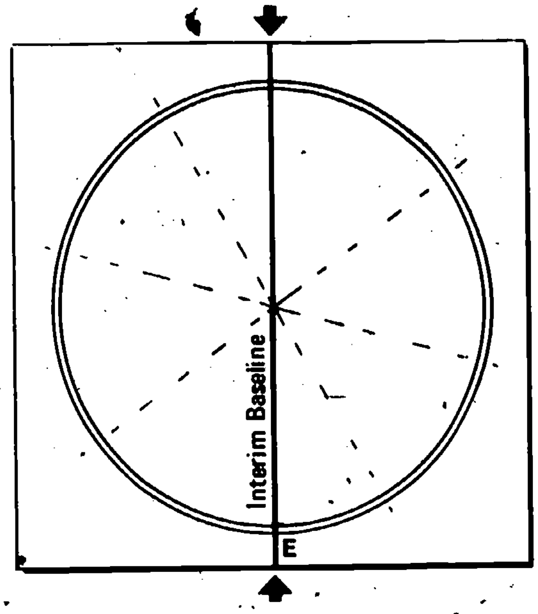
Using the white mounting-board base as a drawing surface, develop a detailed "floor plan" upon which you can erect the basic structure and align the optics. Label all lines and plot points as shown, because these are essential for cutting and assembly.

Remove the shell and plot the center of the outline circles on the base by lightly drawing several diameter lines and marking their centers. Through the center of the circle, draw a centerline from one edge of the base to the other. This will be the interim baseline. Be sure it is perpendicular to the edge of the base at point E.

With the protractor, locate line AD and draw it on the base. Mark points A and D on the base. Now draw line AF and mark point F on the base.

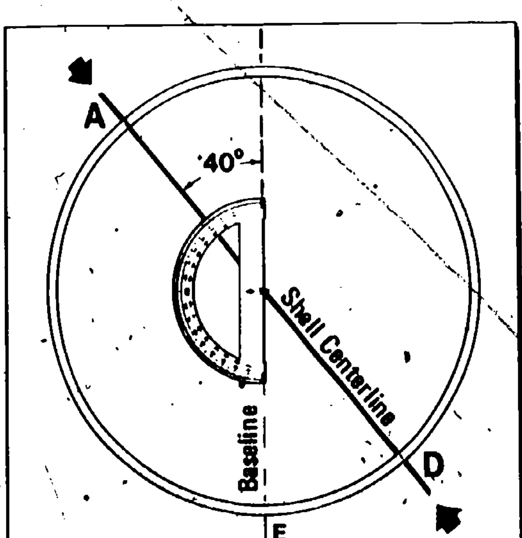


Average the center points of the diameter lines to find the center of the circle.

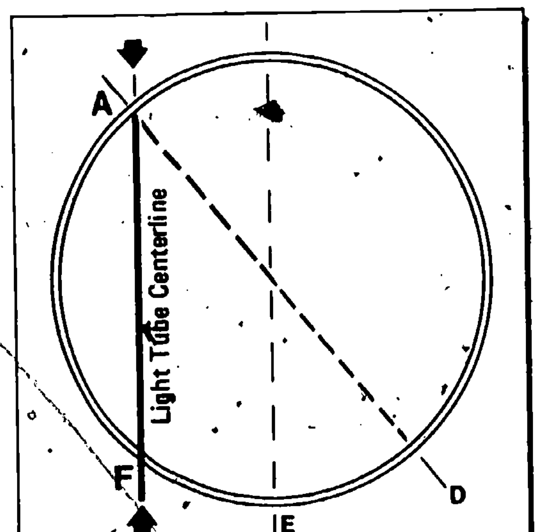



The interim baseline is the starting point for plotting the floor plan. Mark point E at one end of the baseline beside the outer circle.

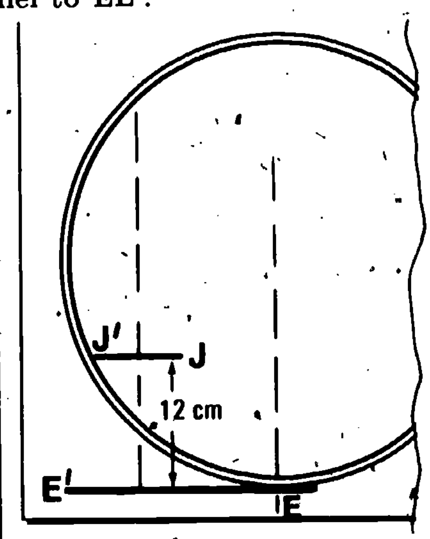
Using the protractor, plot line EE' tangent to the outer circle from the baseline to the edge of the base. Draw line JJ′ 12 cm from line and parallel to EE′.




Point A is where the diffraction grating centerline will be. Point D will locate the hinge line of one door.



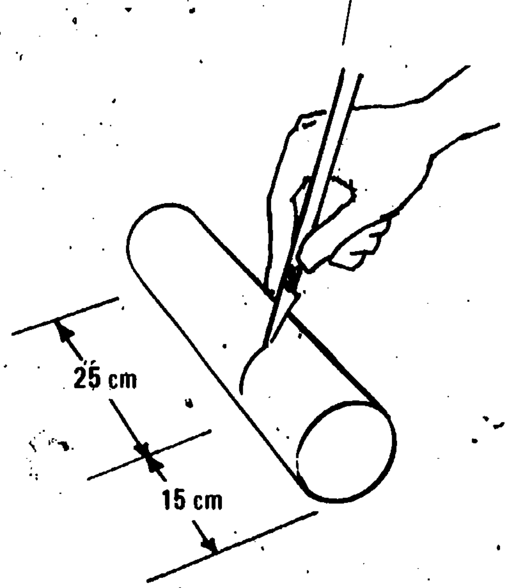

Line AF is parallel to the baseline, and begins at A on the inner circle.

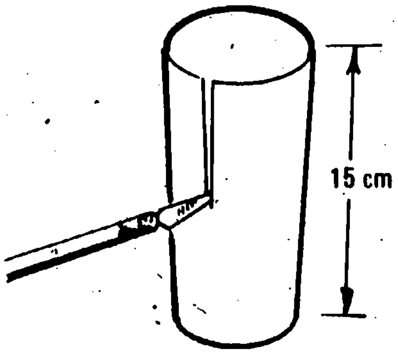



Lines EE′ and JJ′ will be used to locate the light-tube brackets. Before going on with the plan, the diameter of the light-tube guide must be determined.

# 5 Cut and size the light-tube guide

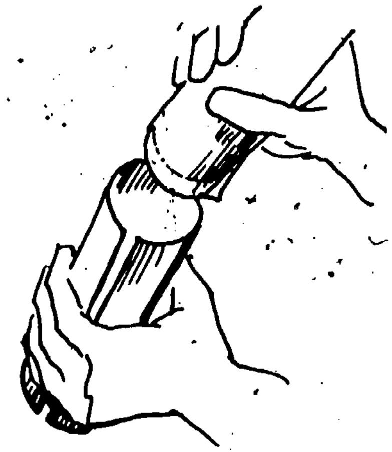
To make the light-tube guide from the cardboard tube, cut one 25-cm piece, and another that is 15 cm long. With the knife, carefully slit the 15-cm piece as shown. This is the light-tube guide.



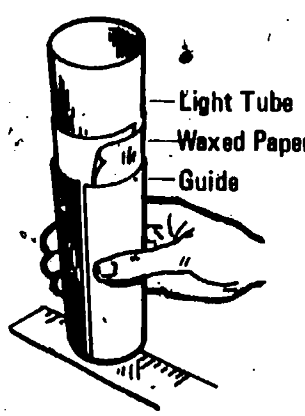

Slitting the Incident Light Tube Guide

Wrap a piece of waxed paper around the 25-cm piece and shove the wrapped tube into the light-tube guide.

Now you're ready to measure the diameter of the light-tube guide.

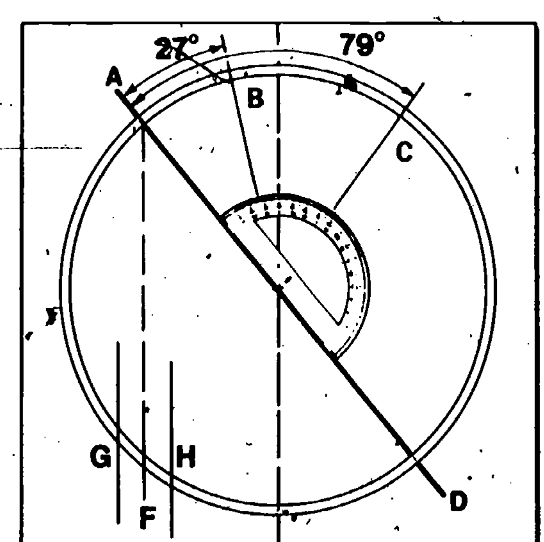
Holding the entire assembly as shown, measure the outside diameter to be plotted on the floor plan. Remove the light tube and waxed paper and save them for later use.




On the floor plan, draw lines G and H. The distance between the lines should equal the diameter of the light-tube guide. G and H should be symmetrical about the line AF. Then draw two lines through the inner and outer circles 2 mm outside of lines G and H and label them G′ and H′. These marks will be used to locate guidelines on the shell to help in cutting the hole for the light-tube guide.

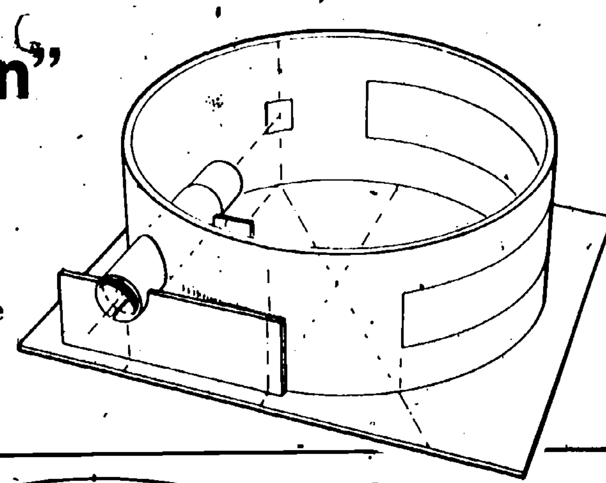
Using the protractor on line AD as shown, mark point B 27° from A, and point C 79° from A.

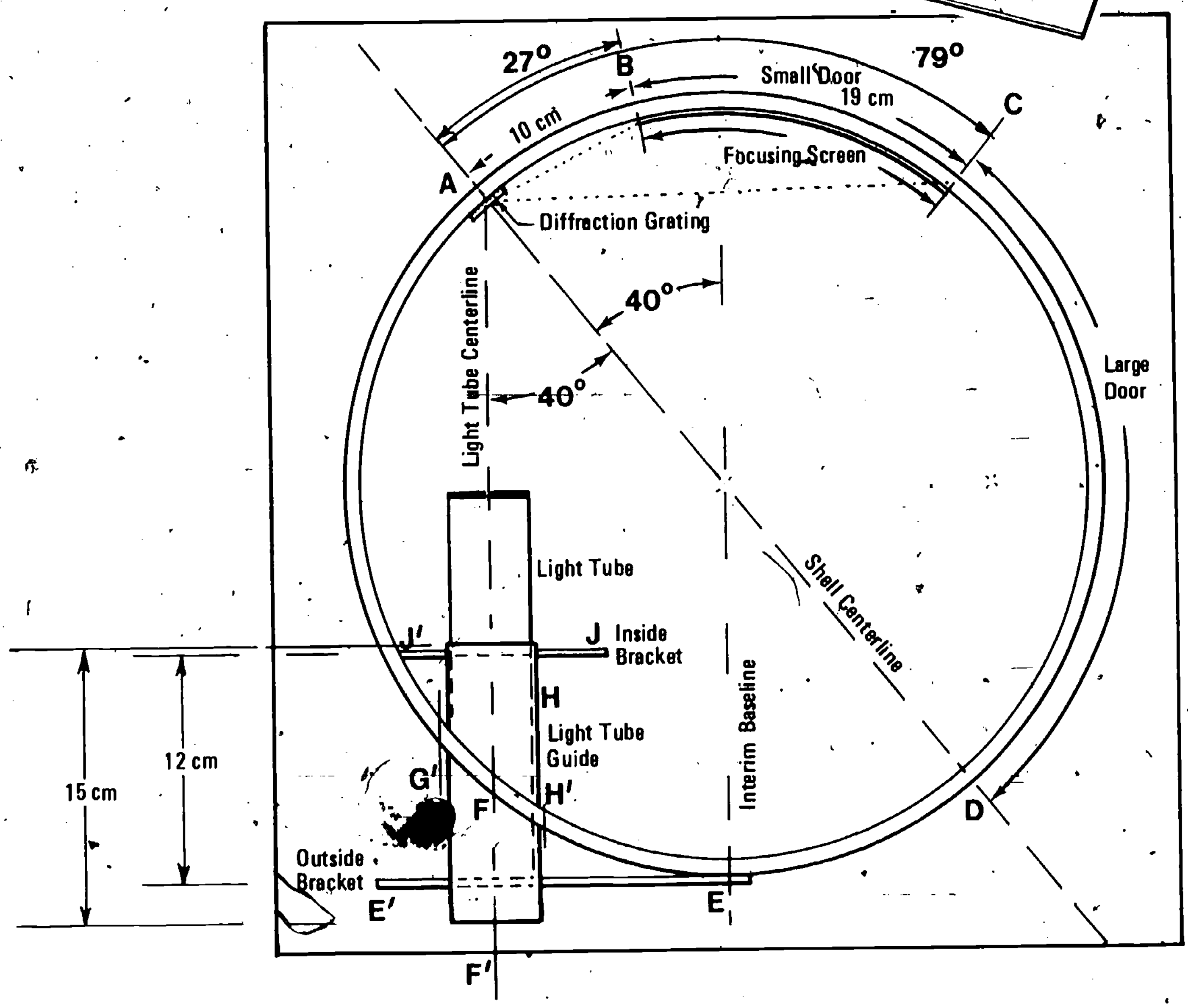
Point B will locate the hinge line of the small door in the shell, and point C will locate the joint between the two doors to be cut in the shell later.

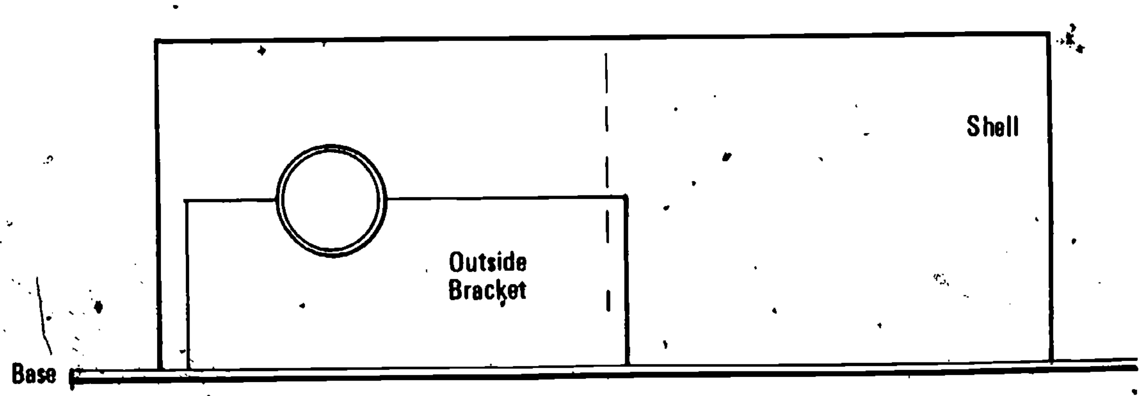


# 6 Check the total "floor plan"

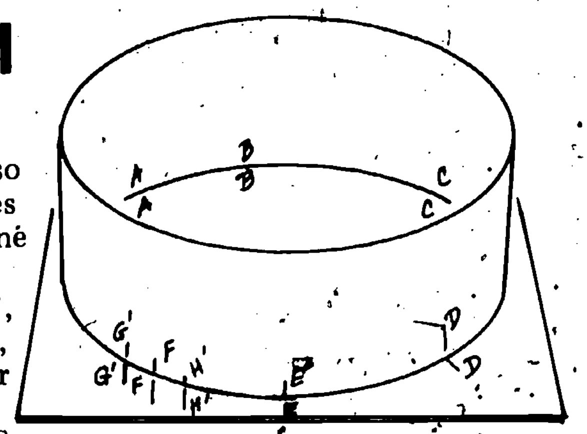
The floor plan is now complete, with all reference points needed to mark the shell for cutting and to place parts for gluing. Before proceeding, check your floor plan against this diagram to be sure all guidelines and reference points have been correctly plotted.





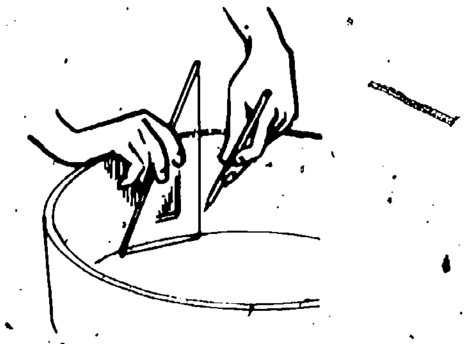



# 7 Mark the shell

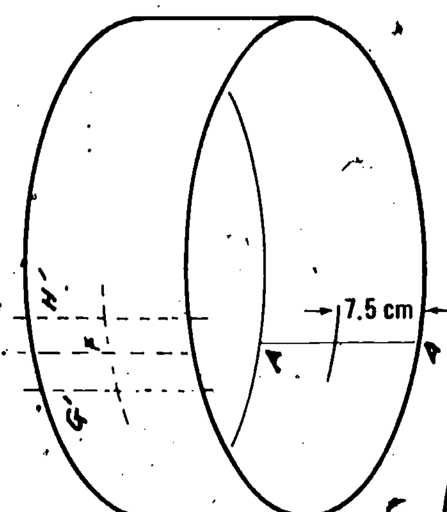



Set the shell back on the base so the shell fits between the circles drawn in Step 3. While someone holds the shell firmly in place, carefully mark points A, G', H', and J on the inside of the shell, and place the appropriate letter beside each mark. In a similar manner, mark points B, C, D, E, F, G', and H' on the outside of the shell.

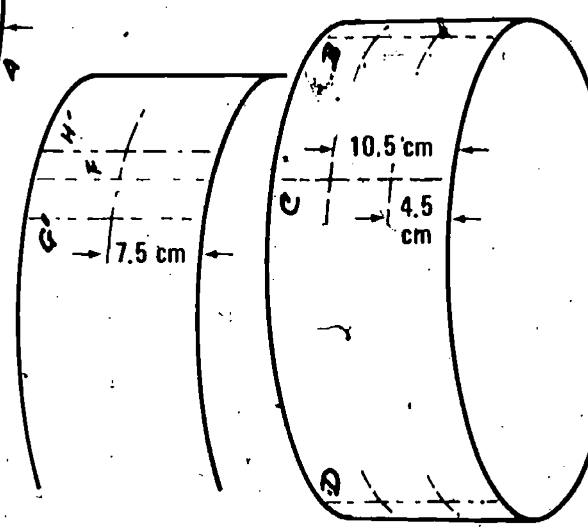
With the triangle resting on the base, draw a vertical line on the shell at each of the points you have marked.



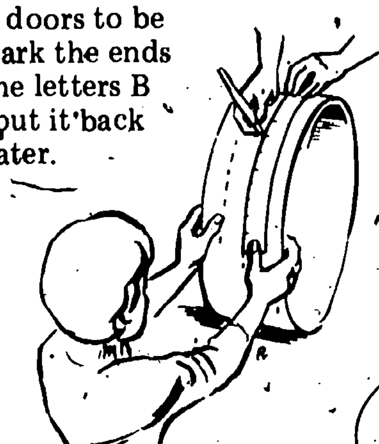
Remove the shell from the base and lay it on its side. On the vertical line on the inside of the shell at point A, mark a point 7.5 cm from the base. Do the same at points G' and H' on the inside and outside of the shell. These points will be used when installing the light tube.




On the vertical lines at points B, C, and D, mark points 4.5 and 10.5 cm from the base.

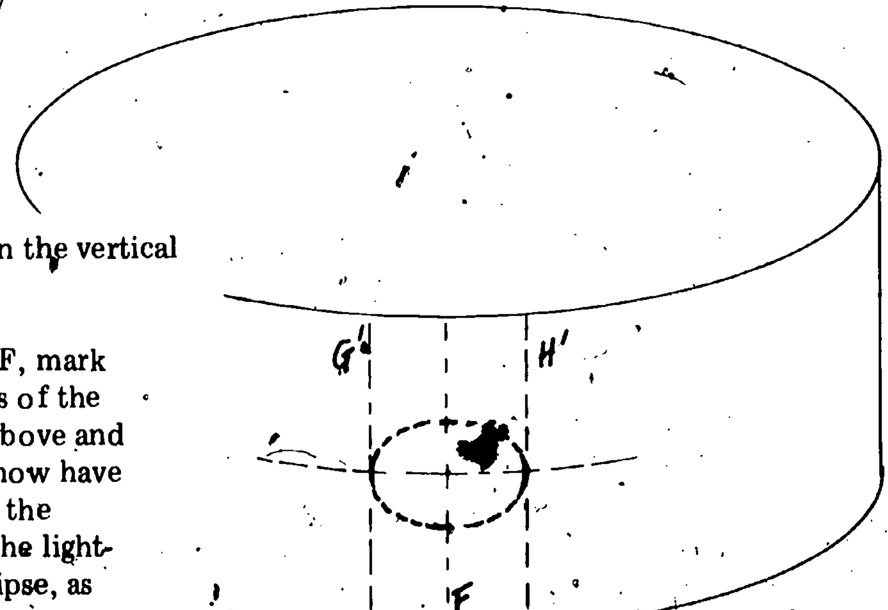



With the flexible straightedge, draw a line connecting the 4.5-cm marks on the vertical lines at points B, C, and D. In a similar manner, connect the 10.5-cm marks. You now have the outlines of the doors to be cut in the shell. Mark the ends of the door with the letters B and D so you can put it back in place properly later.



Connect the 7.5-cm marks on the vertical lines at point G' and H'.

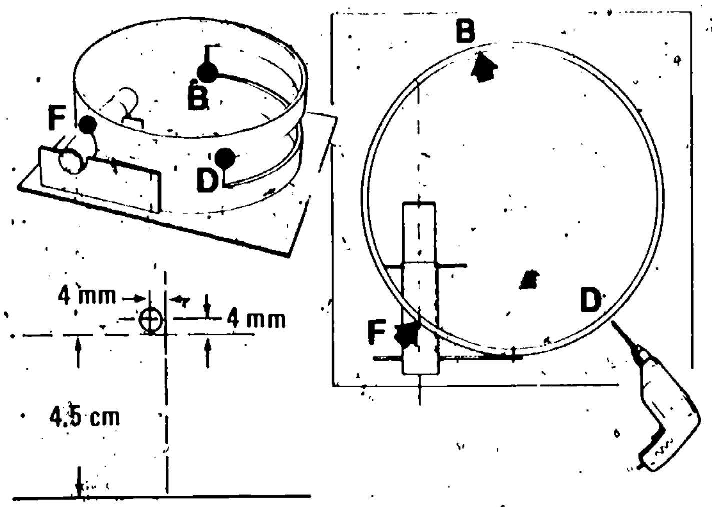
On the vertical line at point F, mark points that are 1/2 the radius of the light tube guide plus 2 mm above and below the 7.5-cm line. You now have the major and minor axes of the ellipse that must be cut for the light-tube guide. Sketch in the ellipse, as shown.



# 8 Drill the shell

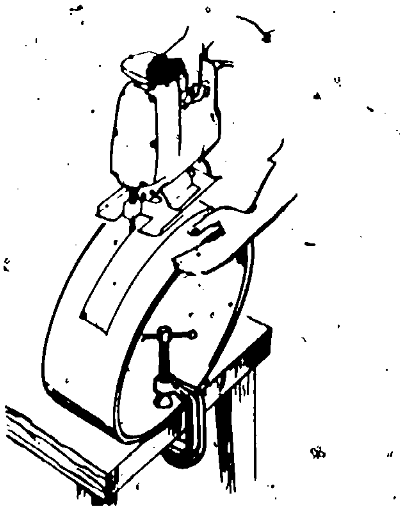
To make drilling more accurate, pilot holes should be provided for the drill bit. With a nail or center punch, put an indentation in the outside of the shell 4 mm from the 4.5-cm line and the vertical drawn at point B. Make second pilot hole 4 mm from the 10.5-cm line and the vertical at point D. Make a third pilot hole 4 mm below the top of the ellipse on the vertical line at F.

Now drill 5/16-in. holes at each of the three points where you made the pilot holes. You are then ready to cut out the doors and the hole for the guide.




# 9 Cut the shell

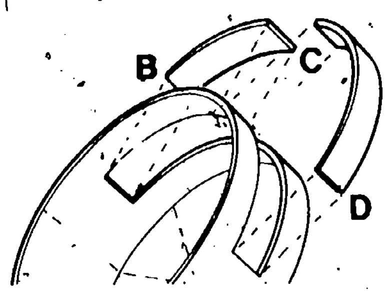
Clamp the ring to a workbench so the doors are at the top. Have someone hold the ring steady while you cut. Insert the saber saw in the hole beside the vertical line at point B and cut along the line to the 10.5-cm line. (If the saw blade is too large to fit the 5/16-in. hole, enlarge the hole along the vertical line with the knife.) Then remove the saw and reinsert it in the same hole, 90° from the first cut, and saw along the line parallel to the base as far as the vertical line at point D.



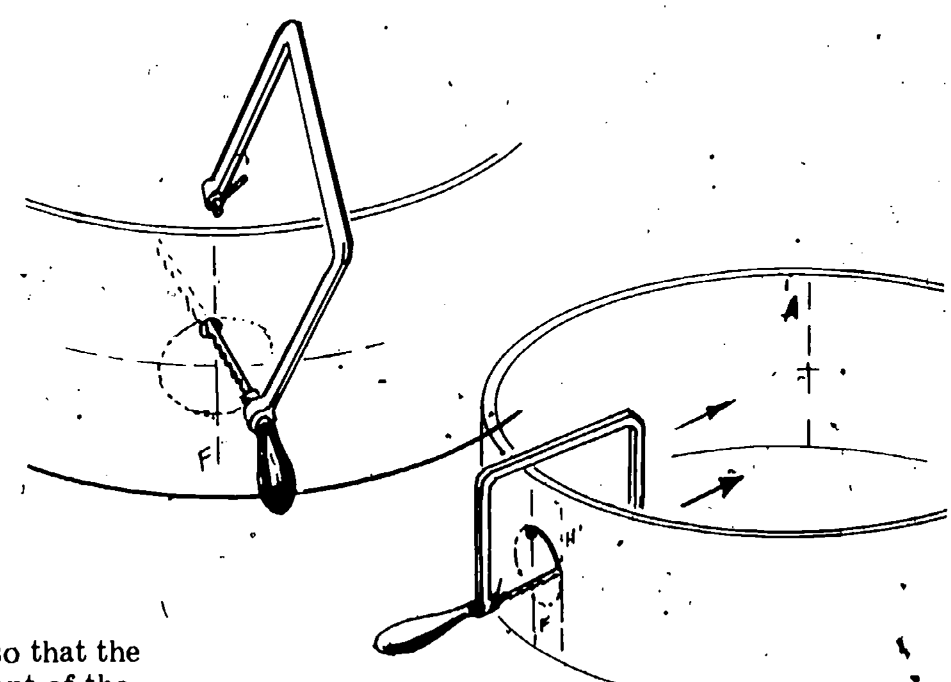
Wait until the sabre saw blade stops oscillating before removing it from the material, and don't switch on the saw for a new cut until the base of the saw rests on the material. When holding the ring steady do not hold the ring with fingers or thumbs in front of the saw blade.

In a similar manner, saw along the two lines from the hole beside the vertical line at point D.

Remove the piece cut out and carefully cut it in two along the vertical line you drew from point C. Set the two pieces aside for later use as doors.



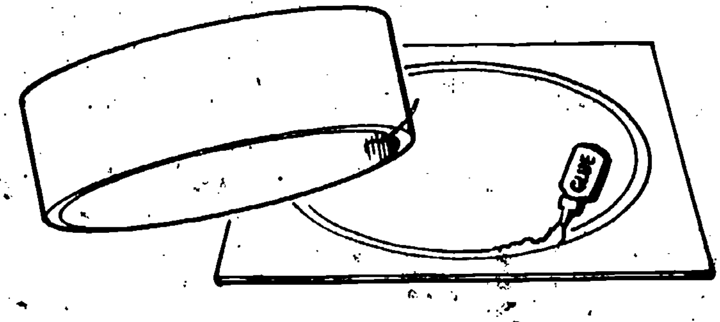

Remove the clamp and set the shell on the workbench in its normal position, with the ellipse at point F toward you. Remove the blade from the coping saw, insert the blade through the hole drilled in the ellipse, and reattach the blade to the saw frame, with the saw handle on the outside of the shell. Have someone hold the shell steady while you saw. Keep the saw aimed at the vertical line drawn on the inside of the shell at point A while you cut along the ellipse. As you go around the curve, it will be necessary to change the angle of the saw blade in the frame.




You are cutting the ellipse oversize so that the elliptical hole will not affect alignment of the light tube. The light leak around the light-tube guide can be prevented by covering the gap with tape after the light-tube assembly is installed and aligned.

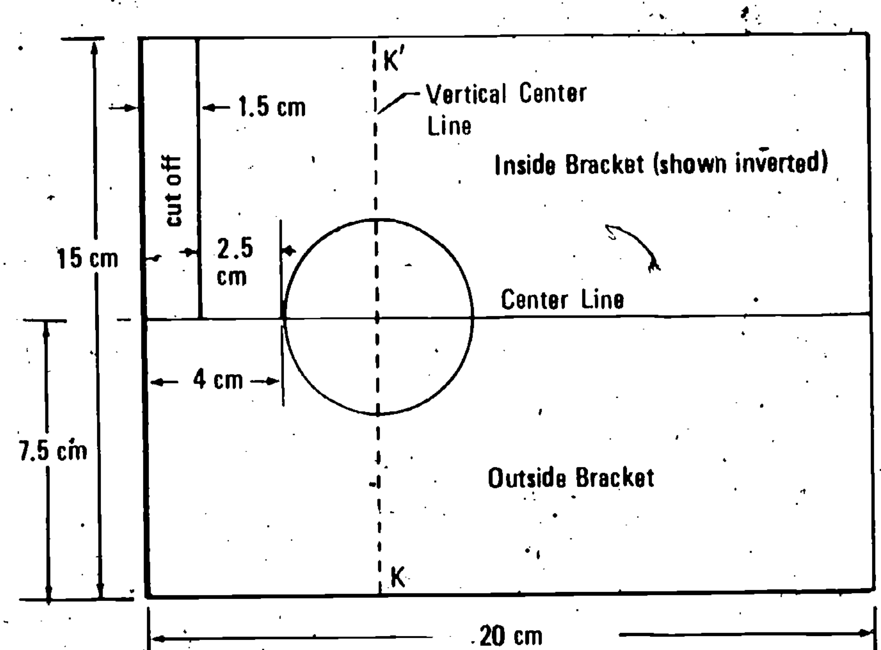
# 10 Mount the shell

Spread white glue evenly between the two circles on the base and on the bottom edge of the shell. Set the shell on the base so that points A, C, D, and F are aligned. Wait for the glue to harden before doing any more work on the base or shell.



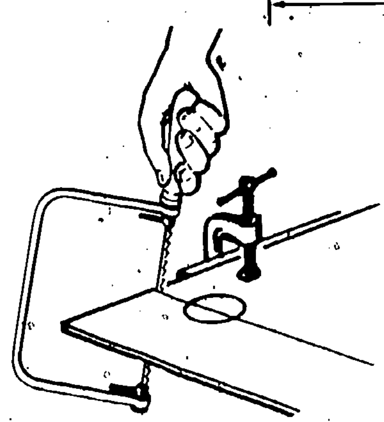
# 11 Make light-tube brackets

From the heavyweight mounting board, cut a rectangle 15 cm wide by 20 cm long. Be sure the long edges are parallel. Draw a centerline on this piece, 7.5 cm from the long edges.



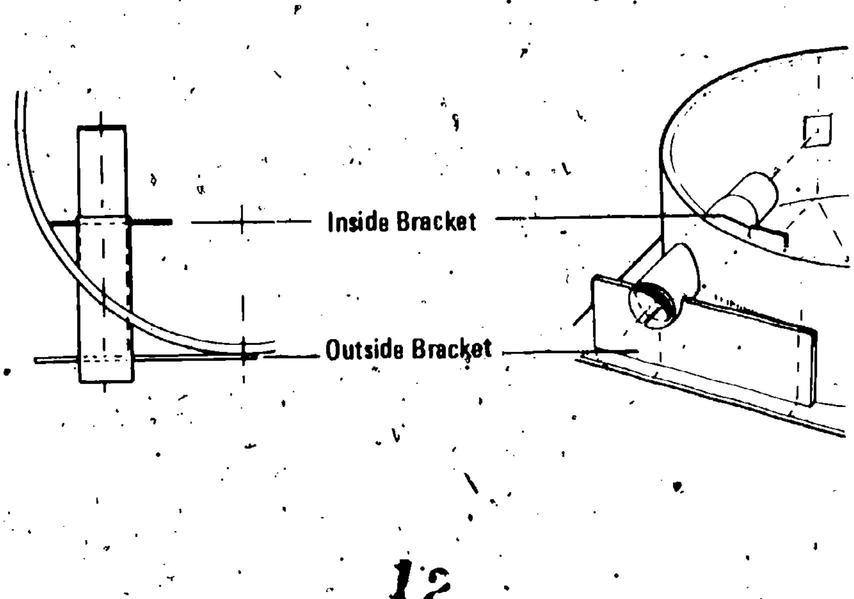

Draw a circle of the diameter you measured in step 5. Center the circle on the center line and locate the circle as shown on the right. Draw a vertical line through the center of the circle to the edges of the board. Label it KK'.

Place the piece of mounting board on the edge of the workbench so the centerline is just off the edge of the bench. Clamp it to the bench to help hold it while you cut. With the coping saw, carefully cut right down the centerline.



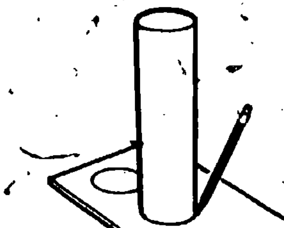
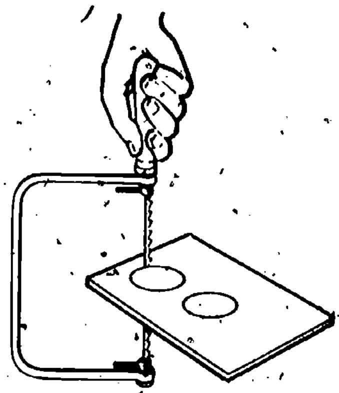
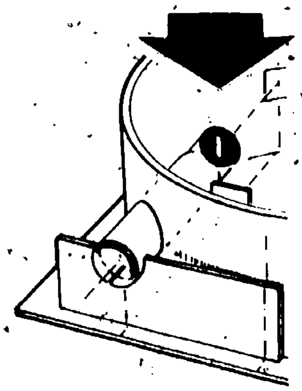
Loosen the clamp and move the piece under it until the semicircle is just clear of the bench. With the coping saw, cut out the semicircle, using the inside of the pencil line as your guide. Remove this bracket from the clamp and place the other piece in position for cutting out its semicircle.

After cutting out the second semicircle, cut 1.5 cm from the end of the piece so that the semicircle is 2.5 cm from the end. Mark this piece "inside bracket." Mark the other piece "outside bracket."

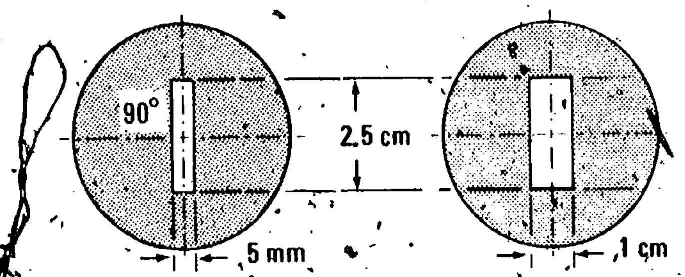


## 12 Make the slit

From the heavyweight mounting board, cut two disks the same diameter as the light-tube. Place the end of the light tube on the board and trace around the tube. With the coping saw, carefully cut out each disk.

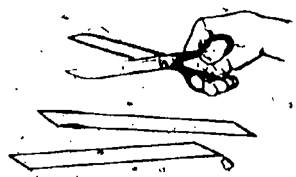
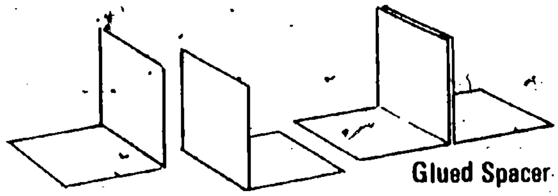




On each disk, draw two centerlines, 90° apart. With the knife, carefully cut a 5-mm slot in the center of one disk, and a l-cm slot in the other, as shown. Each slot should be 2.5 cm long.

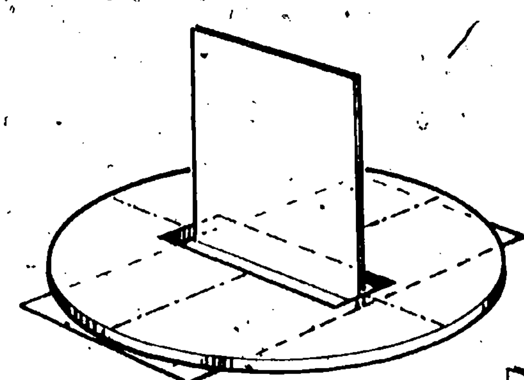



Now put a small piece of masking tape over the sharp edges of the razor blade and carefully break the blade in two along the three holes. Carefully peel off the tape.

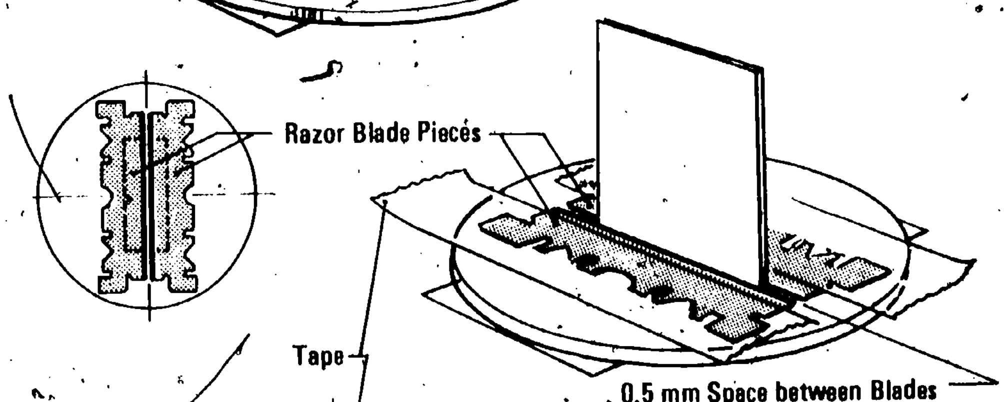

With the scissors, cut two 2.5-cm wide strips, 5 cm long from the file card. Fold each strip in the middle and glue the two pieces together to form an inverted T, as shown.

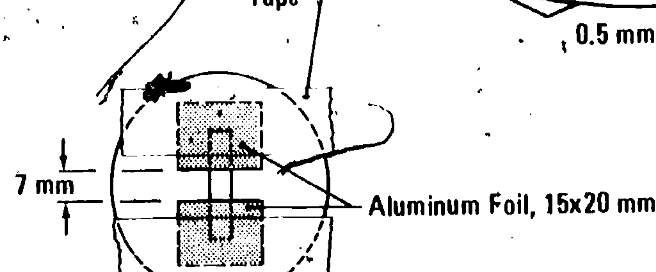

When the glue has set, place the inverted T on a flat surface and put the disk with the 1-cm slot over it so the "stem" of the T is aligned with the centerline of the slot. The inverted T is a spacer to ensure that the razor blades will be 0.5 mm apart when you mount them on the disk.



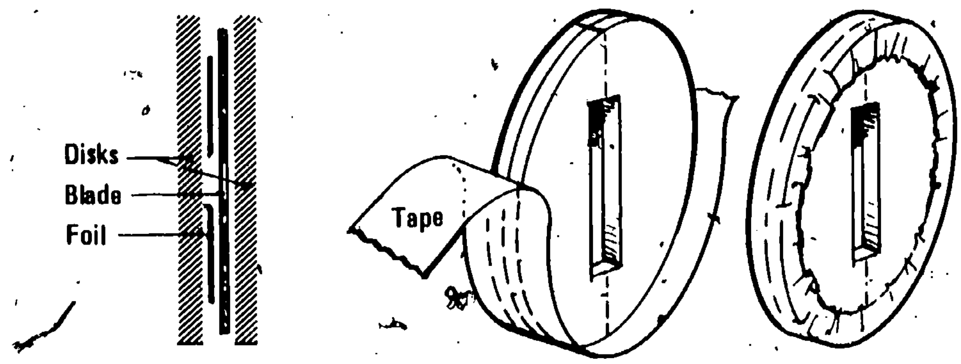
Tape the razor pieces to the disk with mending tape, as shown, pushing them tightly against the spacer. Leave about 2 mm of the blades exposed. With the knife, trim off the tape that extends beyond the edge of the disk. Remove the spacer.



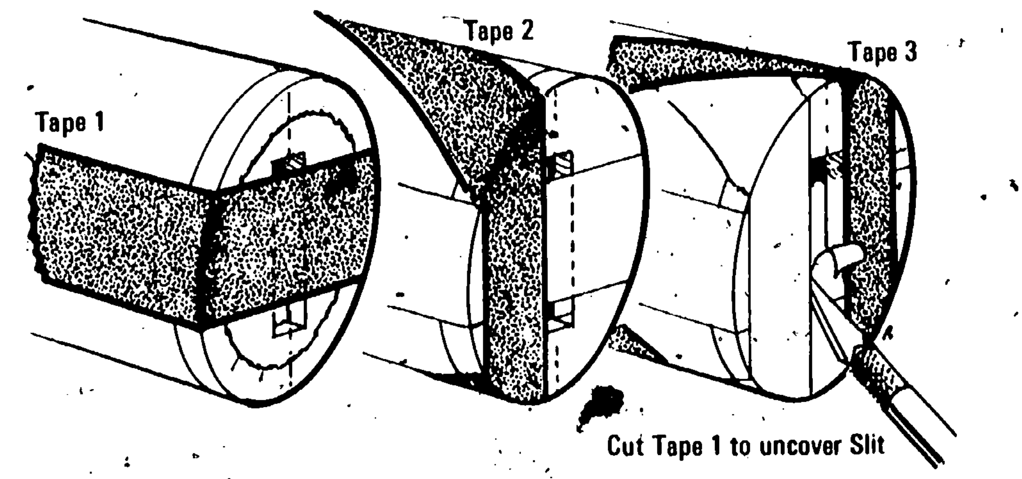

On the disk with the 5-mm slot, tape two 15- by 20-mm pieces of aluminum foil, using the mending tape, so that the slit is 7 mm long, as shown. The foil provides more sharply defined ends for the slit than the cut edge of the mounting board. Be sure the foil is smooth.



Hold the two disks firmly together so the aluminum foil is against the razor blades and the centerlines of the two disks are matched. Fasten the two disks together by taping their edges with masking tape, as shown. Fold the excess tape against each side of the disks to complete their attachment.

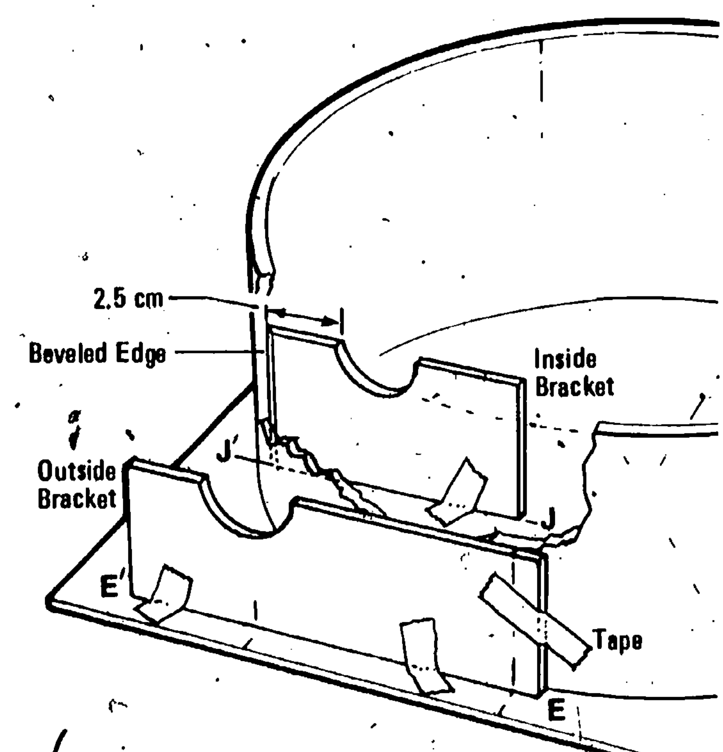



Place the slit disk against the end of the light tube so the 5-mm slot is toward the tube. Tape the disk to the end of the tube with a length of tape across the center of the disk and down both sides of the tube, as shown (tape 1). Place two more lengths of tape alongside the slit and back along the tube (tapes 2 and 3). With the point of the knife, carefully cut away the part of tape 1 that covers the slit in the disk.

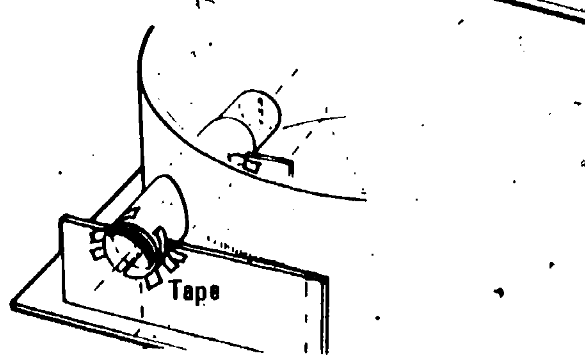



## 13 Install the light tube

Place the inside bracket on line JJ′ so that the semicircular cutout is on top and the vertical centerline K′ is in line with line AF on the baseboard. If the glue has squeezed out from between the shell and the base so that the bracket will not fit tightly against the shell, cut a small triangular piece from the bottom corner of the bracket so it will clear the glue. With the rasp, carefully bevel the end of the bracket so it fits snugly against the shell. Tape the bracket in place with masking tape, as shown.



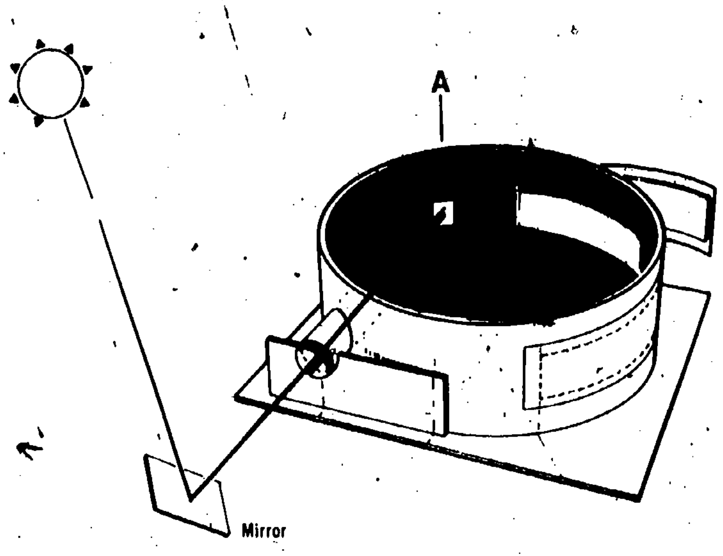

Place the outer bracket on line EE' so that the semicircular cutout is on top and vertical centerline K is in line with line AF on the baseboard. Tape the bracket in place as shown. Wrap the light tube with waxed paper and insert the tube in the light-tube guide. Insert this assembly through the elliptical hole in the shell so that the light-tube guide rests on the brackets. Be sure the slit in the guide is at the bottom. Rotate the light tube until the slit in the disk is vertical. Tape the guide to the brackets, as shown.



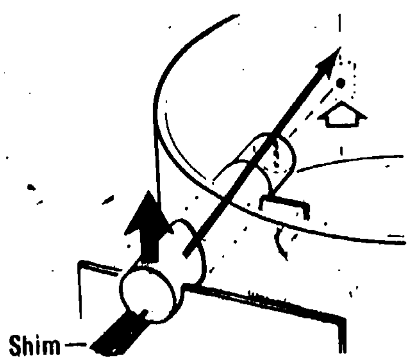
To check the alignment of the light tube, set the spectroscope near a window, but out of the direct light from the window. Have someone hold a small mirror in the sunlight so the light reflected from the mirror shines directly down the light tube.

A simple way to check that the light is shining directly down the light tube is by ensuring that the shadow of the tube on the outside of the shell is symmetrical around the tube.

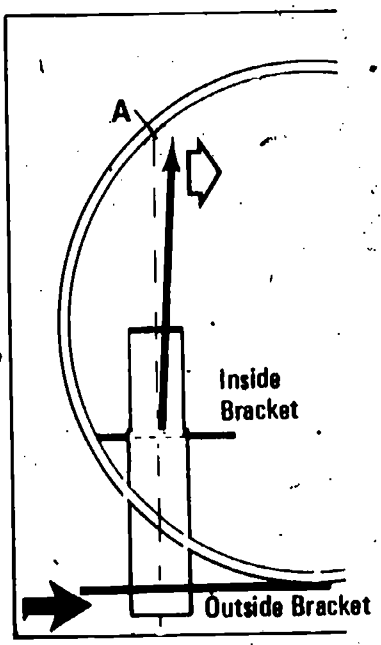
The beam of light from the light-tube slit should strike the inside wall of the shell on the vertical line at point A, centered on the 7.5-cm mark. To darken the inside of the shell enough so you can see the light beam, it may be necessary to partially cover the shell with a piece of cardboard.



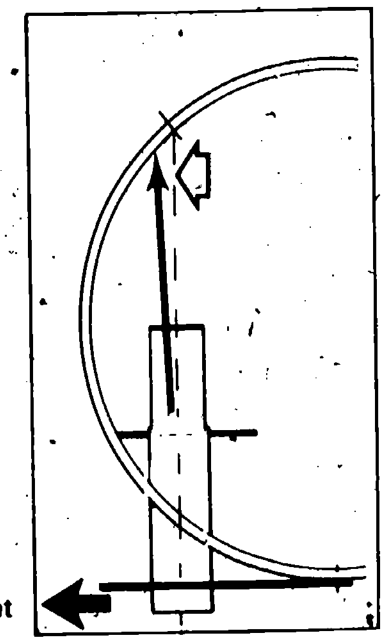

If no sunlight is available, shine a flashlight down the light tube. Be sure the flashlight lens is centered on the end of the light tube. If the lens diameter is much larger than the light tube, you may have to mask off the perimeter of the lens with masking tape.




If the light tube is aimed too high, shim up the tube at the outside bracket with a piece of file card. If too low, shim up at inside bracket.



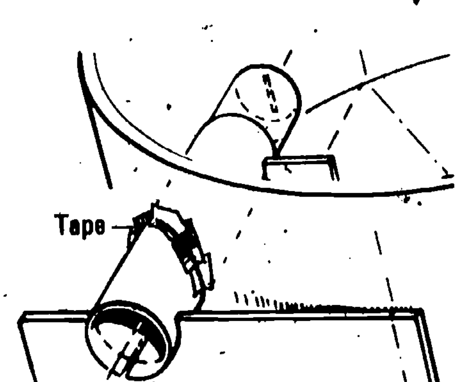

If the light tube is aimed to the right of vertical at A, move outside bracket to the right.



If the tube is aimed to the left of vertical at A, move outside bracket to the left.

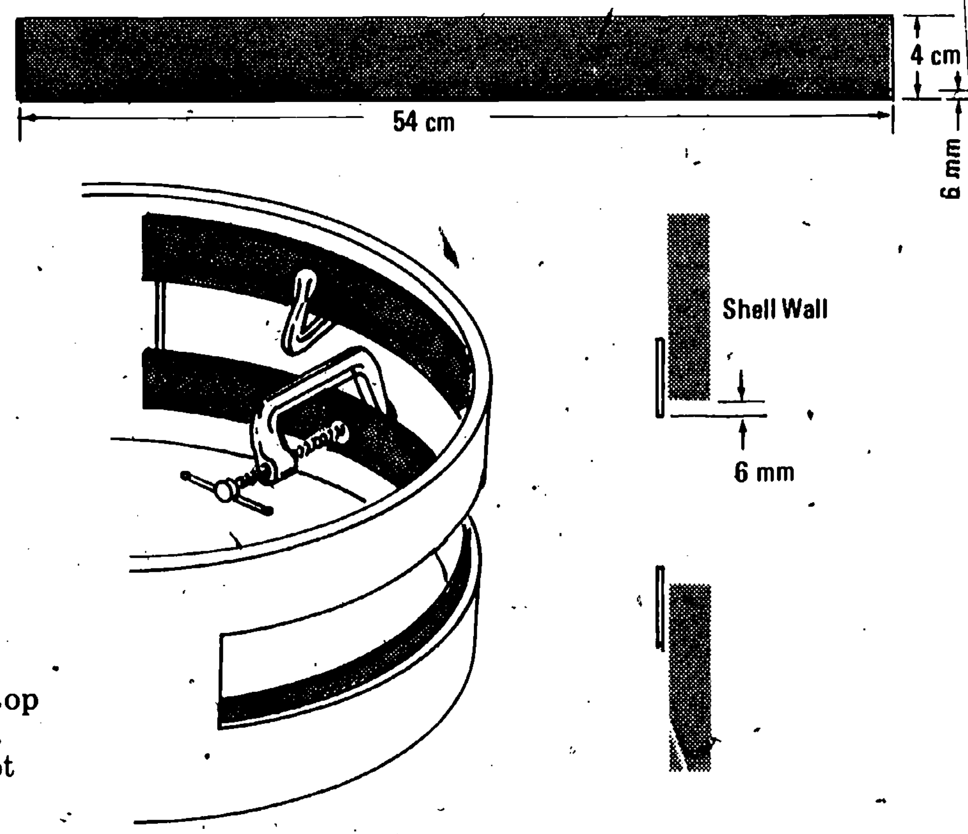
While holding the light-tube guide in the proper alignment, carefully mark the position of the inside bracket on the base. On the light-tube guide, mark the points where the the light-tube guide rests on the brackets. These marks are important to realignment of the light-tube guide when you glue the assembly together.

Coat all mating surfaces of the light-tube guide, shims, inside bracket, base, and shell with glue. Reposition the brackets and tape them in position. Reposition the light-tube assembly and shims (if any) and tape them in place until the glue hardens. As soon as you have everything back in place, quickly recheck the alignment of the light tube and make any necessary adjustments before the glue starts to set up.




When the glue has set, seal up the opening in the shell around the light-tube guide with small pieces of masking tape on the outside of the shell.

# 14 Prepare the doors

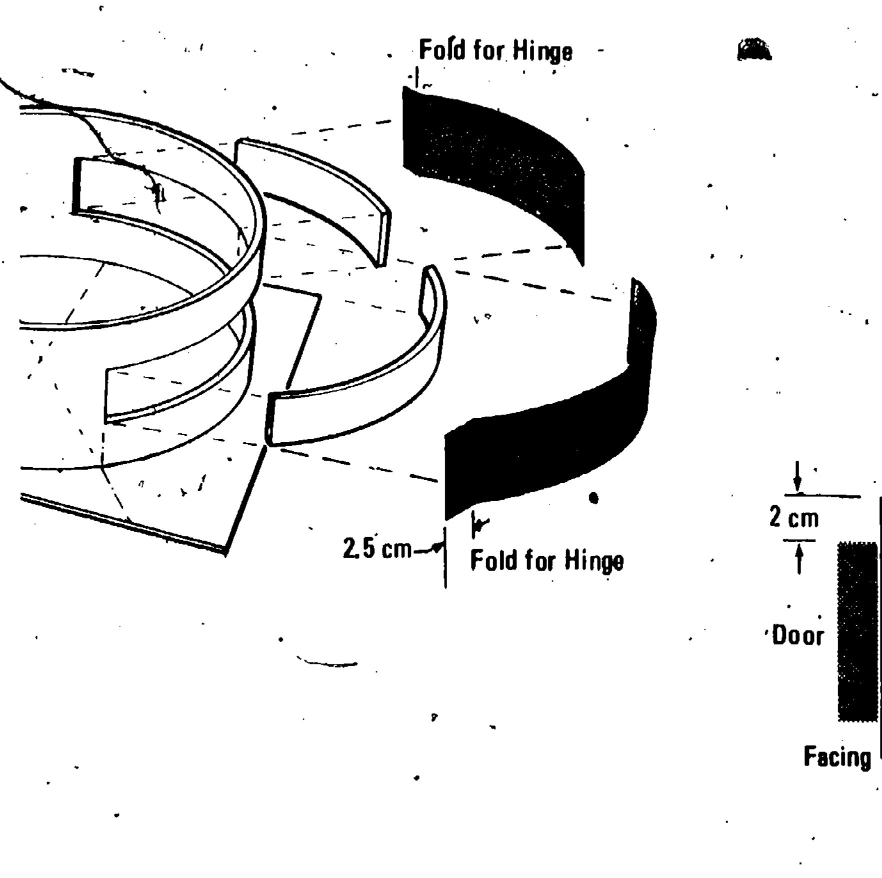



First, you need door jambs to keep the doors from falling inside the shell. Cut two pieces from the heavy mounting board—each 54 cm long by 4 cm wide. Draw a line 6 mm from one edge of each strip.

Glue one of these strips to the inner surface of the shell so that the pencil line is just visible above the bottom of the slot and the strip extends 6 mm above the bottom edge of the slot. Use the C-clamps, slipped through the slot, to hold the strip until the glue sets.

Now glue the other strip along the top edge of the slot in a similar manner. Again, use C-clamps through the slot to hold the strip.

Remove the clamps when the glue is dry.

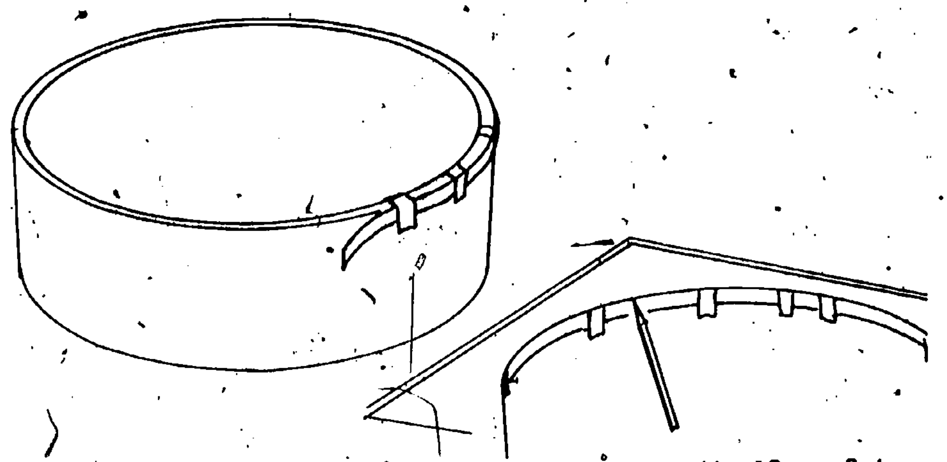



You need facings for the doors before you install them. From the light-weight art board, cut a rectangle 10.5 cm by 21.5 cm. Fold as shown and glue the art board to the outside of the small door so that about 2 cm sticks out above and below the door and the fold is at the end you marked with a B (step 8).

For the second door facing, cut a piece of lightweight art board 10.5 cm by 40.5 cm. Fold the art board 2.5 cm from one end, as shown. Glue this piece to the large door, with the fold flush with the end you marked with a D (step 8). About 1 cm of the facing will protrude beyond the end of the door to overlap the small door to keep the light out.

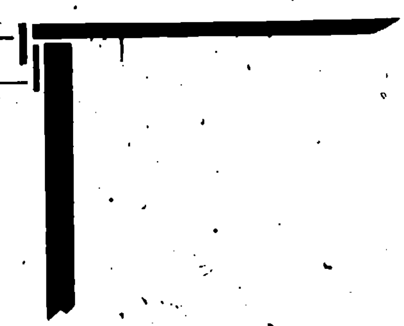
## 15 Make the cover

With the scissors, cut enough 13-mm wide strips of lightweight art board to go completely around the shell. Tape the strips around the outside top edge of the shell to make a spacer. Place a piece of heavyweight mounting board on top of the shell. While holding the board in place, carefully draw around the outside of the spacer so you have a circle on the underside of the mounting board.




Remove the mounting board and turn it over. With the knife, carefully cut along the pencil line to make the circular cover.

Place the cover back on the shell and cut enough 2-cm wide strips from the lightweight art board to go around the outside of the cover as a lightproof rim.



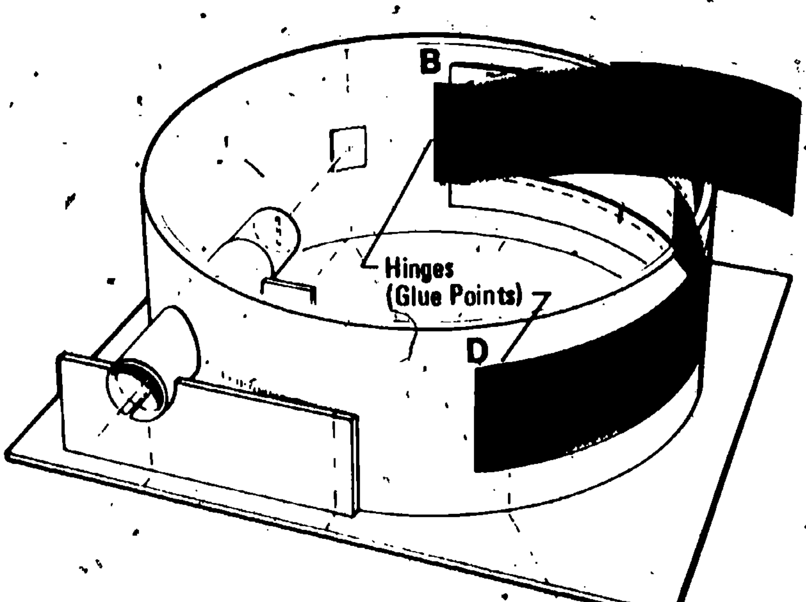

With the spacer trips still attached to the shell, carefully spread glue around the outside edge of the cover only (don't glue the rim to the spacer), and tape the rim strips in place until the glue sets.

When the glue has set, remove the cover assembly and discard the spacer strips. You now have a cover that can be easily removed and replaced.

## 16 Install the doors

When the glue on the door facings has dried set the two doors in the slot in the shell.

With the ends of the doors firmly against the shell wall, apply glue to the folded "hinges" (shown at right as black areas at points B and D). Fasten to the outside of the shell with masking tape until the glue sets.

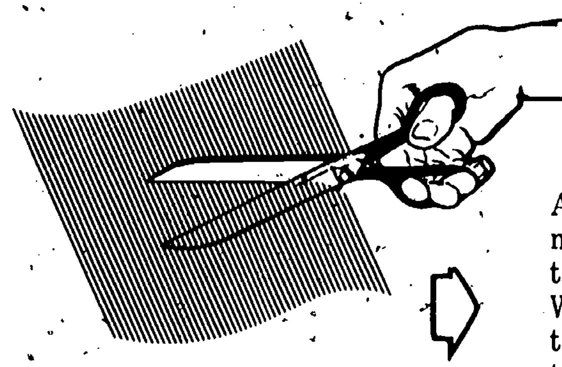



## 17 Paint the spectroscope

To avoid getting paint on the slit, remove the light tube before painting. Paint the inside of the shell, doors, base, and cover with flat black paint to cut down reflection of light inside the instrument. Place 25 mm square of masking tape on the inside of the wall centered on the vertical line at point A where you make the mark 7.5 cm from the base. This will avoid getting point on this area as you need this reference point to mount the diffraction grating. The paint can be applied with a brush or a spray-can.

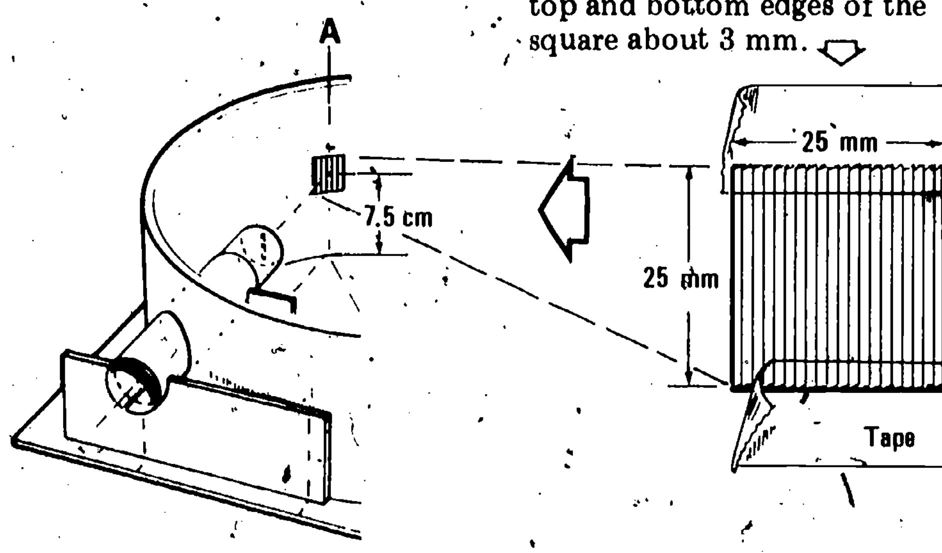
# 18 Install the diffraction grating

Cut a 25-mm square from the sheet of diffraction grating with the scissors. Be very careful not to get any fingerprints on the 25-mm square or on the rest of the sheet. A piece of thin tissue paper or vellum over the sheet of grating will protect it while you handle it. Be sure the line pattern extends all the way across the 25-mm square you cut out.



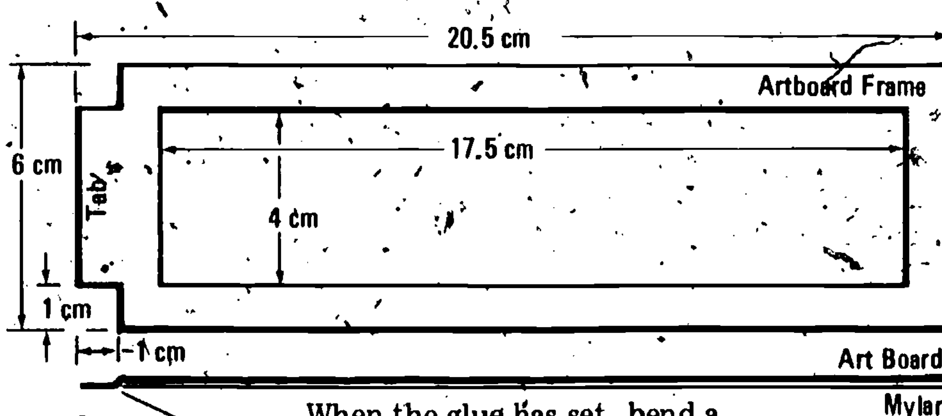
Attach two 25-mm strips of mending tape to two edges of the 25-mm square, as shown. With the line pattern vertical, the tape should overlap the top and bottom edges of the square about 3 mm.

Mount the grating on the inside of the shell so the lines are vertical and the square is centered on the vertical line at point A and the 7.5-cm mark. The line pattern must be vertical. This is hard to measure. The best way is to set up the triangle as in step 6 and align the line pattern on the grating with the vertical edge of the triangle. Again, avoid putting your fingers on the grating material.




# 19 Make the focusing screen

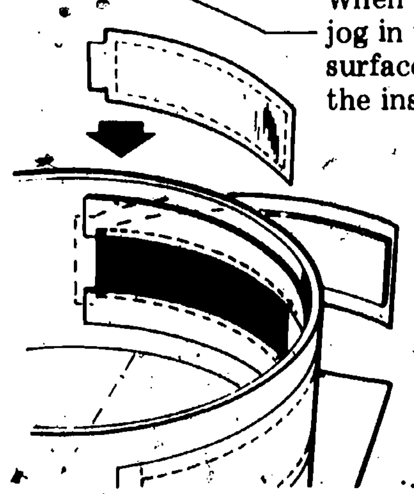
Cut a rectangle of drafting Mylar that is 6 by 19 cm. Make a frame for the Mylar by cutting a piece of lightweight art board that is 6 by 20.5 cm. From the center of this piece, cut a rectangular hole and make a tab on one end, as shown.




Glue the Mylar to the frame, leaving the tab on the frame exposed.

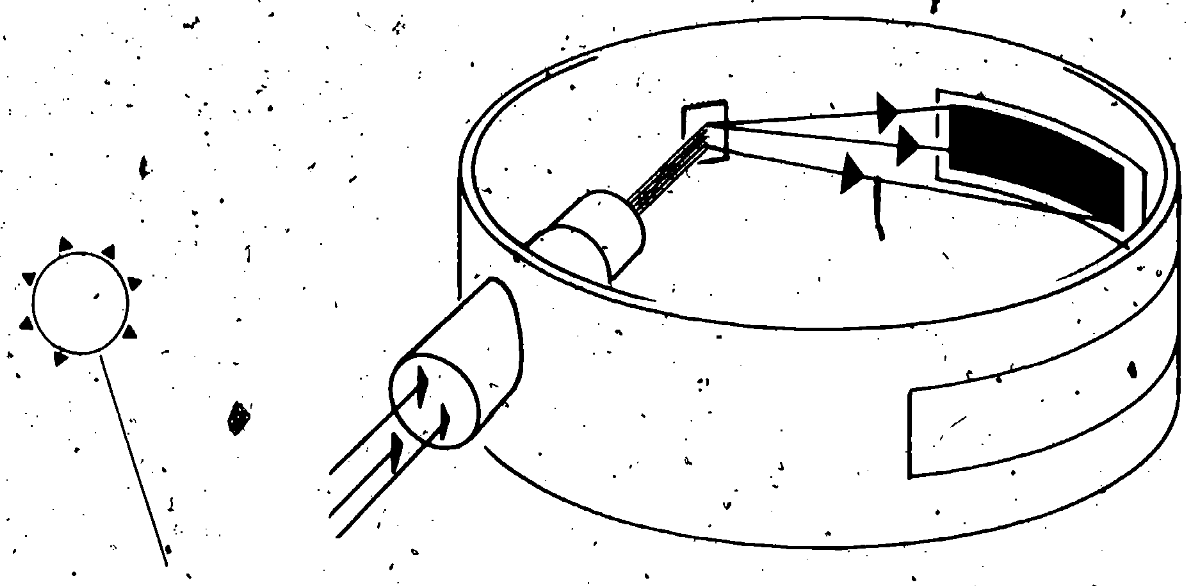
When the glue has set, bend a jog in the tab so that the outside surface of the tab is in line with the inside surface of the Mylar.

Insert the focusing screen in the slot behind the small door. Tuck the tab inside the wall of the shell at the grating end of the slot. The Mylar surface should rest against the door jambs, and the left-hand end of the screen will be trapped under the end of the large door.

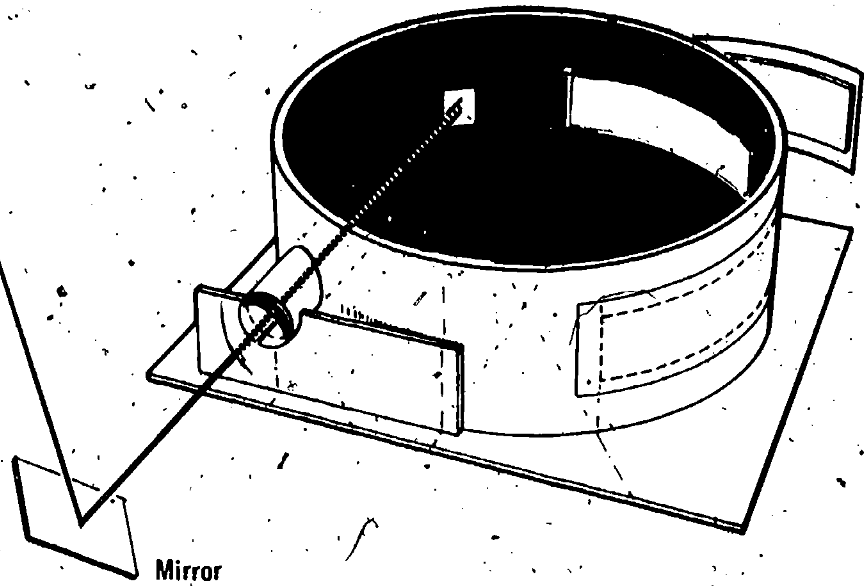


18

# 20 How to use the spectroscope



Reinstall the light tube and you are ready to use the spectroscope. Set the instrument near a window, but out of direct light from the window. Place a small mirror in the sunlight so that light is reflected directly down the light tube. Hold the mirror in place with masking tape.



Mirror

With the spectroscope cover removed, focal-plane door open, and focusing screen in place, adjust the attitude of the spectroscope so that the image of the slit in the light tube is visible in the center of the diffraction grating, but not on any part covered by the mending tape. Rotate the light tube until the image is vertical. Without disturbing the instrument, replace the cover.

A bright spectrum should be visible on the focusing screen, with the red end nearest the grating.

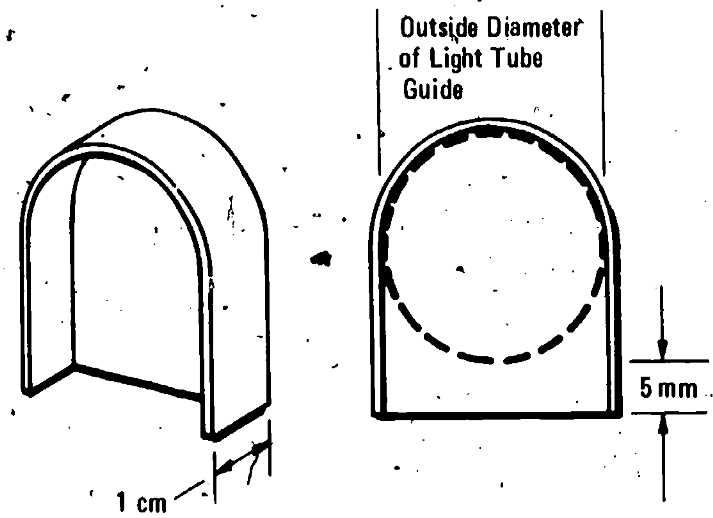
You may need to darken the room with drapes or increase the shade in which the spectroscope is placed and thus increase the brilliance of the spectrum.

# 21 How to make a color print of the spectrum

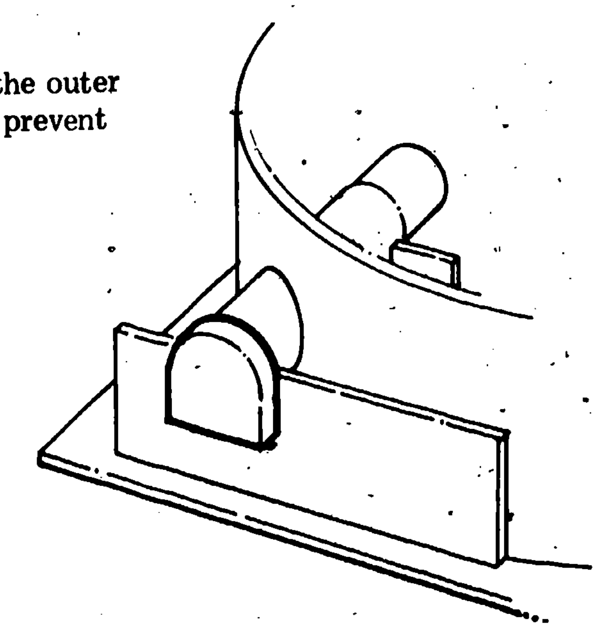
If you want to make color prints of the spectrum your instrument produces, you first must have a means of controlling the light entering the instrument. A cap must be made to place over the outside end of the light tube.

Cut a piece of lightweight art board the width of the light tube guide and about 5 mm longer. This is the cover of the light tube. Cut one end into a semicircular shape, wrap a 1-cm-wide strip of light weight art board around the cover and glue it to the cover to make a rim.

Paint the inside black to cut down on light reflection.

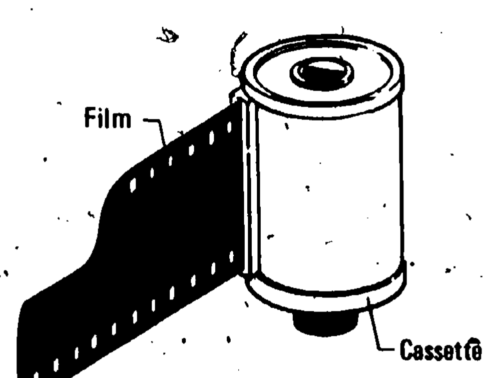



This cap can now be hung on the outer end of the light tube guide to prevent light entering the slit.



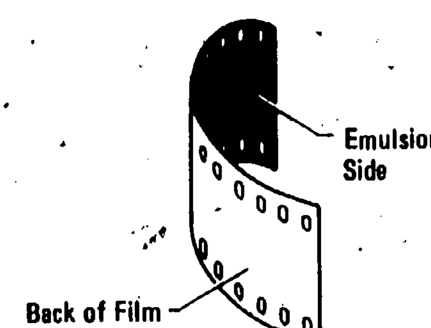
Next the film must be loaded in the instrument. *This must be done in total darkness.*

Take the instrument, a roll of mending tape, a cassette of color film (preferably Kodacolor X Film), and a pair of scissors into a darkroom. As all subsequent activities must be done by feel, it would be a good idea to practice removing the cover from the shell, opening and closing the doors, and taking out and replacing the foscusing screen with eyes closed. When confidence in all these activities has been developed, the lights can be turned out.

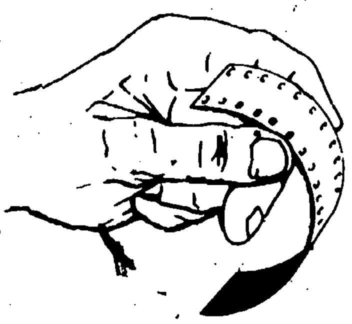



Take the focusing screen out of the instrument. Pull some film out of the film cassett. Remember that the first few centimeters of the film are shaped as shown in the sketch. It is a shape that you will easily recognize by feel.

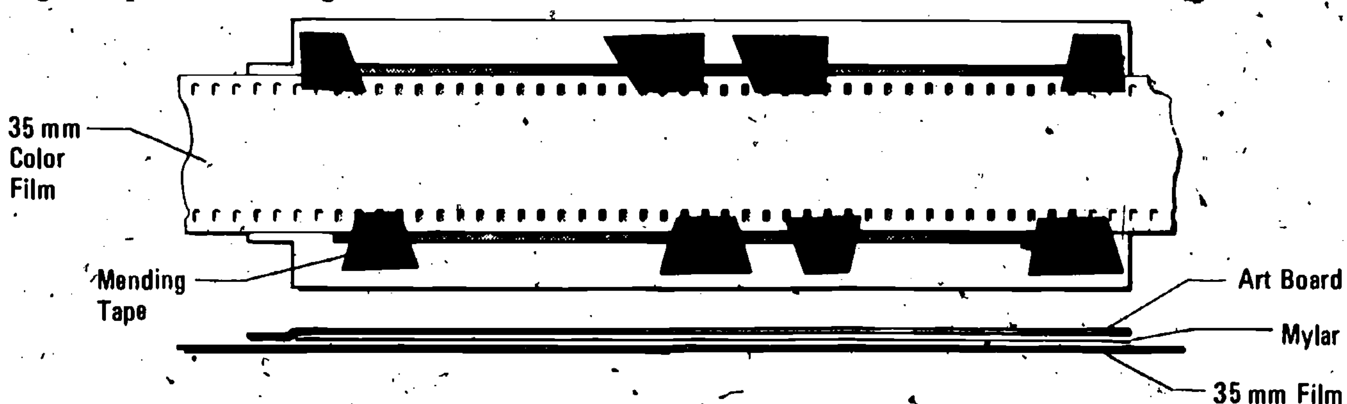
Now pull out enough of the *full width* film to stretch the full length of the focusing screen. While doing this be careful not to touch the emulsion of the film. It is easy to tell which side of the film has the photographic emulsion. The film has a natural curl, and the emulsion is always on the inside surface.



Allow the film to curl up and you will immediately know which is the side that must not be touched. It is best to hold the film lightly by the edges.



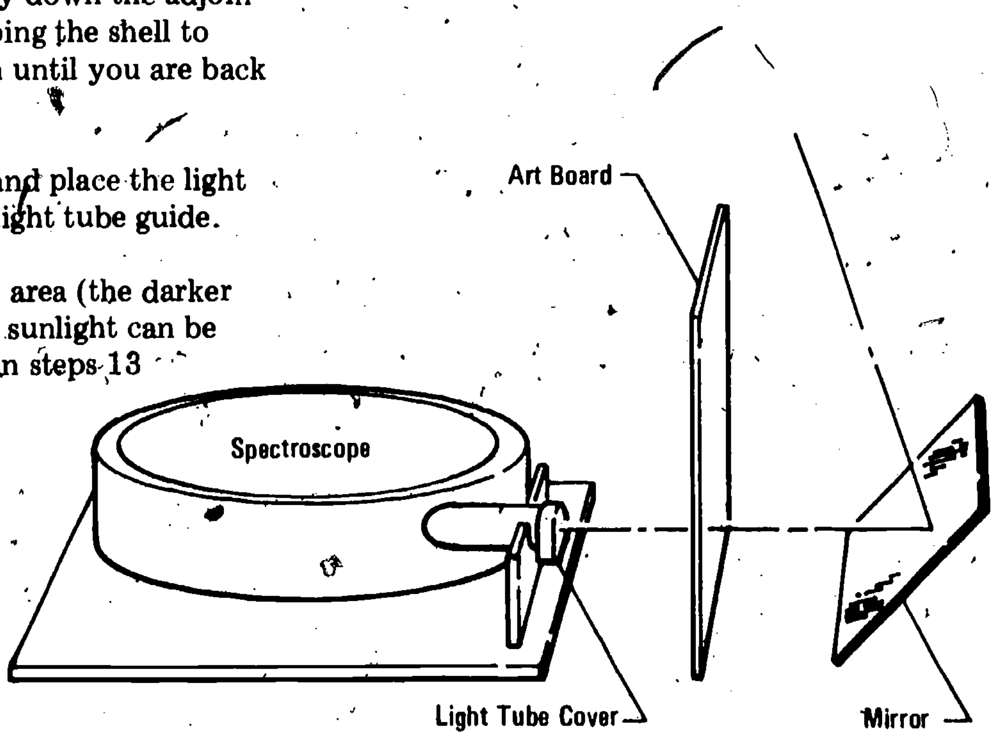
Cut off a piece of film the same length as the focusing screen. The back of the film must be toward the mylar surface. Use a number of short lengths of tape to attach the film. It will be easier than trying to tape the full length. Do not allow the tape to extend inward beyond the rows of perforations on the film. Any tape adhesive or finger prints on the photographic emulsion will spoil the development of the photograph.




Place the focussing screen in the instrument as described in step 19. Close both doors and put a strip of masking tape all the way down the adjoining edges of the doors, overlapping the shell to make sure the doors don't open until you are back in the dark room.

Replace the cover on the shell and place the light tube cover over the end of the light tube guide.

Take the instrument into shady area (the darker the better) in a position so that sunlight can be reflected into the light tube as in steps 13 and 19. When the mirror is set up so that the light is shining on the light tube correctly, place a piece of lightweight art board between the mirror and the instrument so that the reflected sunlight now falls on the card. Carefully remove the light tube cover.




Now quickly take away and replace the piece of art board so that the sunlight was reflected into the instrument for half a second. Then quickly replace the light tube cover and take the instrument back to the darkroom and turn out the light.

Remove the film from the focussing screen and pack in a light proof container so that it can be safely taken to a film processing lab. Kodacolor X is a film negative process. Therefore you should ask for contact prints to see the spectrum in its natural colors.

# APPENDIX: What is a Spectroscope?

## Objectives

The objectives of this appendix are to:

1) give the reader an understanding of the principles of refraction and diffraction;
2) show that the apparently crude instrument that can be built using the instructions in this booklet differs only in quality from the more sophisticated instruments used in advanced scientific programs.

In the text that follows, descriptions of optical principles are interspersed with some simple calculations that define the theory behind the principles. These are indented and printed in smaller type so that readers who are not mathematically inclined can skip over them without interrupting the narrative.

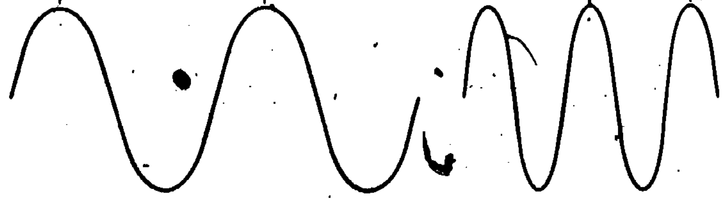
## What is a spectroscope?

A spectroscope is an instrument that separates light from a luminous source into the array of colors (wavelengths) of which the light is composed.

### The Spectrum

The array of colors is called a *spectrum*. The white light from the Sun is really a mixture of different colors. Red, orange, yellow, green, blue, indigo, and violet are considered to be the colors in the spectrum of visible sunlight. The rainbow is the best-known result of separating the Sun's white light into a spectrum. The "colors of the rainbow" are not in seven distinct bands; but merge into each other. This is called a *continuous spectrum*, and is illustrated on the outside back cover of this book.

Light has a wave formation similar to ocean waves. The distance between crests in light waves (the wavelength) varies, as it does in ocean waves. Light of one wavelength differs in appearance from light of another wavelength. For example, red light has a longer wavelength than violet light. In the cover illustration the wavelengths of various colors can be measured by comparison with the wavelength scale below the continuous spectrum. The wavelengths of light are extremely short and are usually measured in units called *angstroms* (Å).* An angstrom is one ten-millionth of a millimeter.




### Emission Spectrum

When a material is heated until it begins to vaporize, it radiates light. The type or color of the light radiated by one chemical element differs from the light radiated by any other element. For example, when a sample of the metallic element sodium is vaporized, as in an electric arc, the light emitted (radiated) is bright yellow.

If a spectroscope is used to spread out the light from the heated sodium, the spectrum that is observed is not a yellow band, as might be expected, but is a pattern of narrow yellow lines. These lines represent specific wavelengths of light, and the pattern of lines is unique to the element sodium. This is called an *emission spectrum*. Each element has its own specific pattern or line spectrum.

As shown on the outside back cover, the emission spectrum of mercury has lines in the blue and yellow wavelengths of the visible spectrum. When you look with the unaided eye at the light from vaporized mercury, it has the blue appearance that can be seen in many streetlights. This is because your eye has "added together" the colors and brightnesses of the emission spectrum, and the blue component is brighter than the rest.

### Absorption Spectrum

If the white light from a source like the Sun is passed through a vaporized element and then into a high quality spectroscope, a pattern of dark lines can be seen in the continuous spectrum from the light source. The vapor has absorbed light at specific wavelengths. The wavelength of these lines correspond exactly to the wavelengths of the light emitted by the same element when vaporized. The spectrum containing the dark lines is called an *absorption spectrum*. See Figure A-1.

The phenomena of emission and absorption spectra are discussed in more detail in the wall

*Named for A. J. Angstrom, a Norwegian physicist, who first measured wavelengths of light in 1868.

chart *The Spectrum*, NF-54/1-75, the booklet *The Spectrum*, NF-55/1-75, and in *Modern Physics*, and other texts listed in the bibliography.

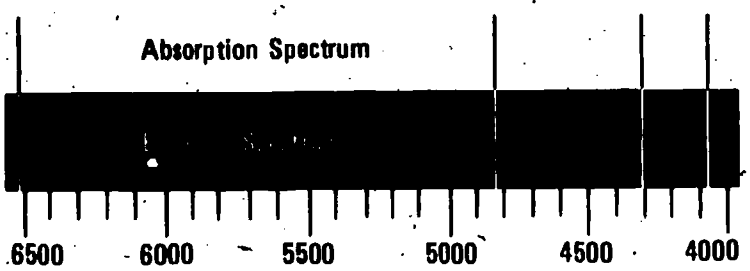



*Figure A-1 Absorption and Emission Spectra of Hydrogen*

## Methods of Generating Spectra

Spectroscopes employ one of two basic methods of generating spectra—refraction or diffraction. The method with which you may be most familiar uses a prism of transparent material, and the optical principle by which it works is called *refraction*.

Refraction—When a succession of equally spaced light waves strikes a material like glass, the waves are slowed down as they enter the material, and the direction of travel is bent toward a line perpendicular to the surface. See Figure A-2.

If the approaching light is traveling at a velocity, represented by $V_1$, and its angle from the perpendicular is $\theta_1$; and if the velocity inside the glass is $V_2$, and its angle is $\theta_2$:

$$\frac{V_1}{V_2} = \frac{\sin \theta_1}{\sin \theta_2}$$

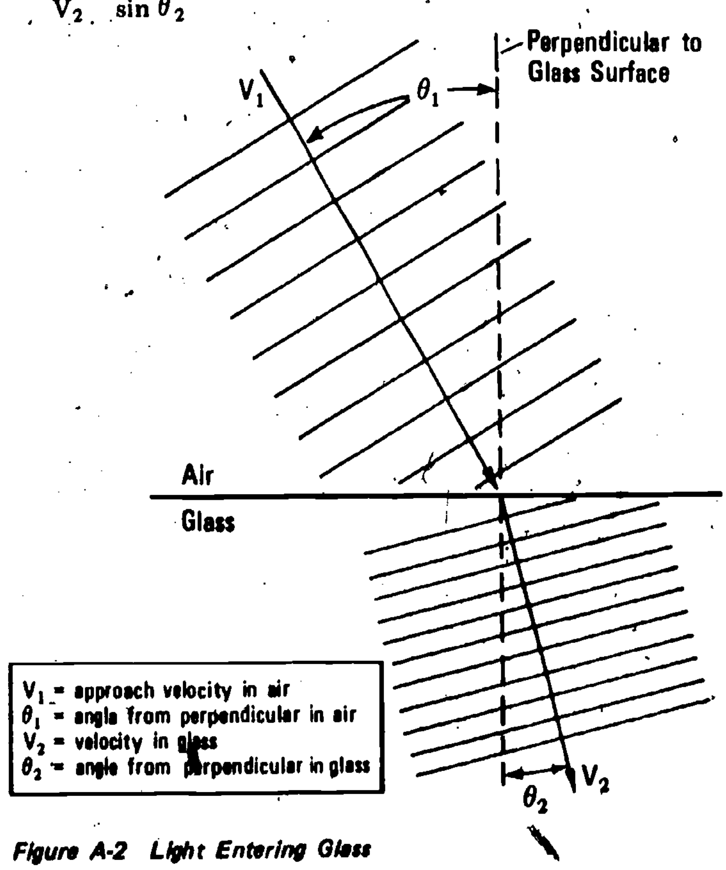



*Figure A-2 Light Entering Glass*

This bending of the light is called *refraction*. The term *refractive index* is used to indicate the amount of bending as light passes from one medium, like air, into another, like glass. The refractive index varies with the velocity at which the light travels in each medium.

When the light passes through the other surface of the glass, the waves speed up to the velocity they had before entering. The light is bent, again away from the perpendicular. If the surfaces of the glass are parallel, the entry angle ($\theta_1$), will be the same as the exit angle ($\theta_4$), as shown in Figure A-3.

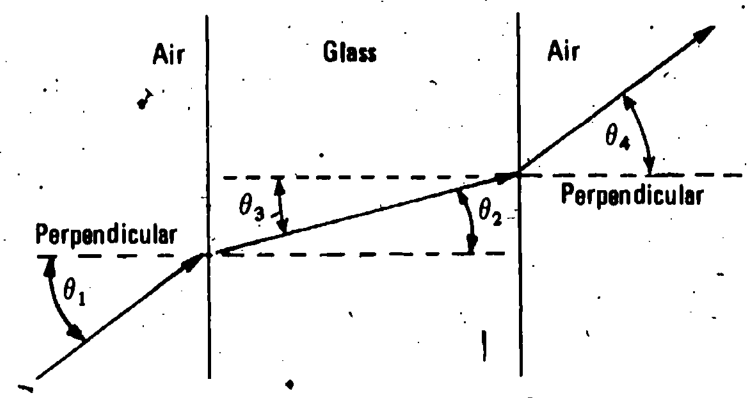



*Figure A-3 Refraction through a Sheet of Glass*

When the entry and exit surfaces are not parallel, the light is refracted twice in the same direction. The light still bends toward the perpendicular on the way in, and away from it on the way out, but the perpendiculars to the surfaces are not parallel to each other (Figure A-4).

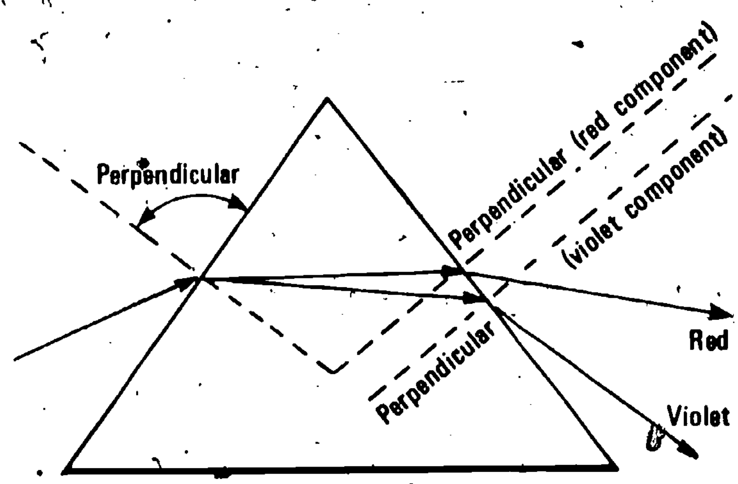



*Figure A-4 Refraction through a Prism*

The refractive index varies with the wavelength of the light—long-wavelength light is bent less than short-wavelength. The colors of which white light is composed—red through violet—have different wavelengths. Red has the longest and violet the shortest. Therefore, when white light (as from the Sun) is refracted through a prism, the red component emerges at a different angle than the violet. This explains why the spectrum of white light becomes visible when the light is passed through a prism (Figure A-4).

Diffraction—The second method of generating spectra in a spectroscope is an application of the principle of diffraction. Diffraction is best illustrated by the situation shown in Figure A-5.

A hi-fi speaker is emitting a sound in one room (A). A listener in the other room (B) out of sight of the speaker can still hear the sound because the sound waves are bent after passing through the doorway. It is as if the sound were coming from the doorway and were radiated in all directions.

Other waves behave in the same way. Diffraction of water waves can be easily demonstrated in a ripple tank. The diffraction of light waves across an edge is not as easy to demonstrate because of the much shorter wavelength, but it does occur.

Transmission Diffraction—When a source like an electric light bulb shines, it radiates light in all directions. And, as light is a wavelike phenomenon, an expanding series of waves spreads uniformly in all directions, just like the ripples that spread when you drop a stone into a still pond.

Consider an object like a metal plate, placed where light can shine on it along a line perpendicular to the surface, and consider a small area of the plate that is illuminated by a narrow ray of light. The crest of each light wave of this ray will strike the plate at exactly the same time across the width of the wave.

When such a ray of light strikes a plate containing two narrow slits, some of the light emerges through the slits (Figure A-6). The slits, like the doorway, become sources of light of the same wavelength as the source on the other side of the plate, and the crests and troughs of the light waves emerge exactly in phase with those falling on the other side of the plate. Light passing through each slit radiates in all directions. In Figure A-6, the light waves striking the plate and emerging from each slit are represented by alternate solid and dashed lines. The solid lines represent crests and the dashed lines represent troughs.

The circular arcs of crests and troughs centered on each slit intersect each other. In some cases, crests radiating from one slit intersect crests radiating from the other, and troughs intersect troughs. These light waves are said to be in phase with each other, and the light energy in one wave reinforces the energy in the other (wave plot A in Figure A-6). This is called *constructive interference*. Careful examination of the figure shows that this occurs in three directions. One line is perpendicular to the plate and joins the intersection points where

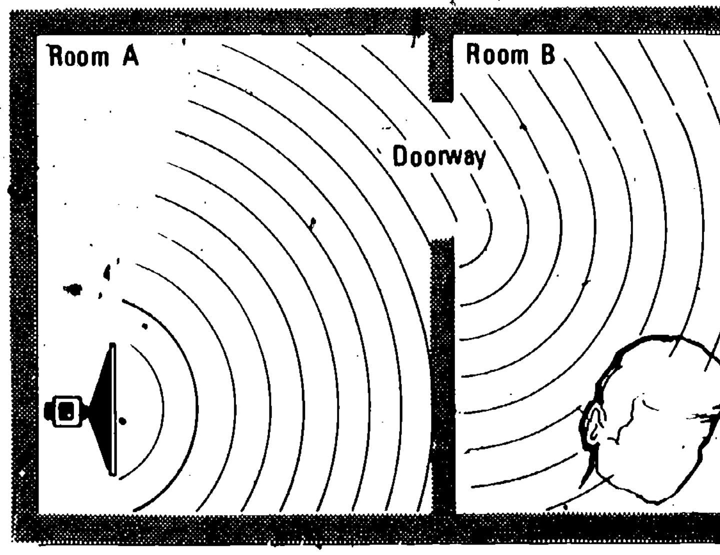



*Figure A-5 Diffraction of Sound between Two Rooms*

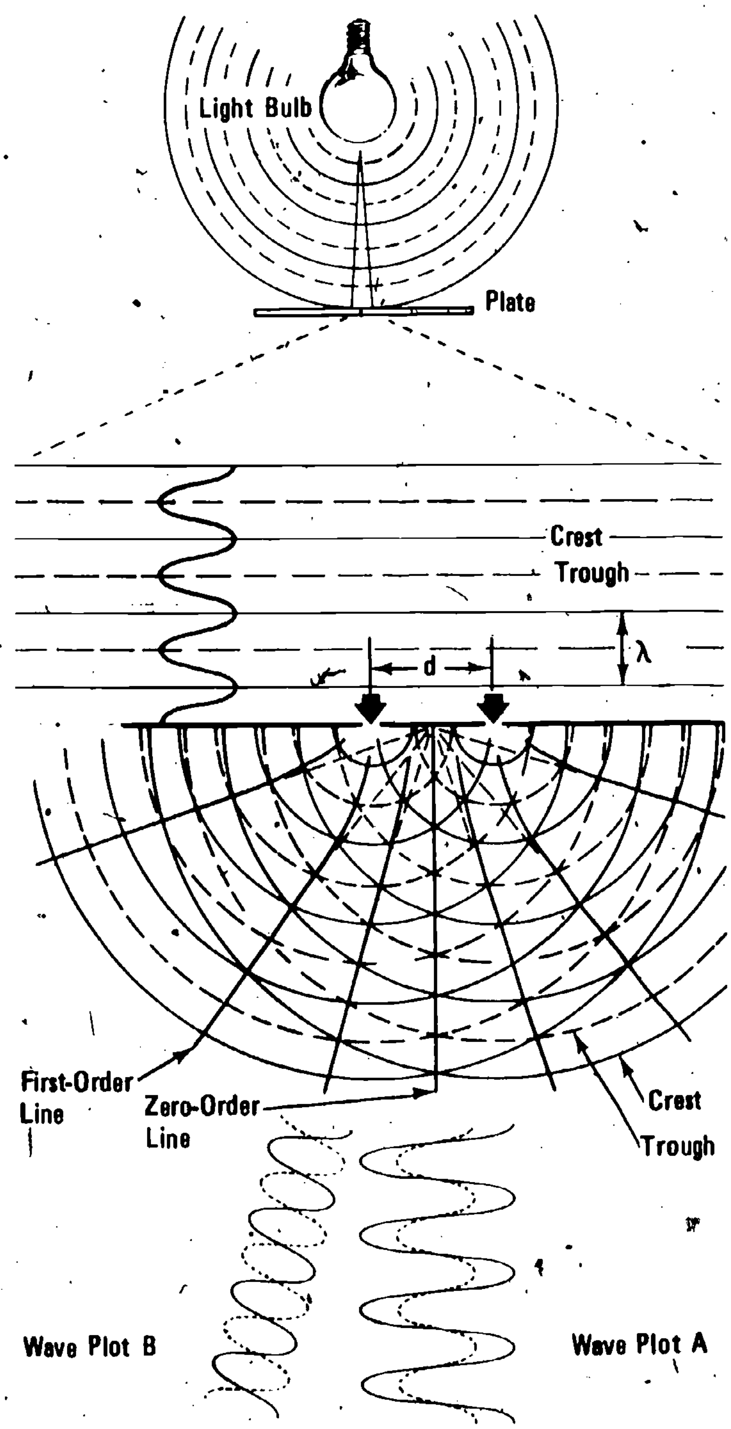



*Figure A-6 Diffraction through Two Slits* the number of wavelengths from each slit is equal. (One wavelength is the distance from one solid line to the next.) This is called the *zero-order line*.

The other two lines are symmetrical about the zero-order line. These lines connect intersections where the distance from one slit to the intersection is one wavelength greater than the distance from the other slit. This is called the *first-order line*. The shape of each of these lines along which crests reinforce each other is called a *hyperbola*. If plotted for a few dozen wavelengths, each hyperbola will become tangent to a straight line that intersects the plate at the base of the perpendicular (zero-order) line.

Where the wave crests intersect with troughs, the waves are out of phase, and the light energies cancel each other (wave plot B). This is called *destructive interference*. These lines are also hyperbolas. Replotting Figure A-6 and eliminating the wave patterns, we get Figure A-7. The angle between the zero-order line and the tangent to the first-order line is called the *interference angle*. This angle varies with the wavelength of the light, just as in the prism discussed earlier. Here, the longer the wavelength, the greater the angle. (The opposite was true for the prism.) The important fact is that the colors are separated. The interference angle also varies with the distance between slits.

The sine of the interference angle ($\theta$) is given by the equation:

$$\sin\theta = \frac{n\lambda}{d}$$

where

$n$ = the order (0, 1, 2, etc)

$\lambda$ = wavelength of the light

$d$ = distance between slits (in the same units as $\lambda$).

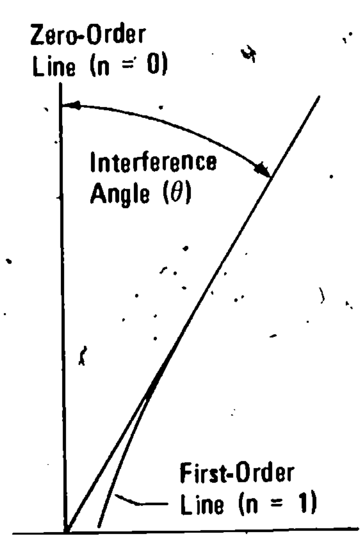



*Figure A-7 Interference Angle*

In Figure A-6, which is an exaggerated diagram, the wavelength ($\lambda$) is the distance from one solid line to the next and equals 8 millimeters. The distance between slits (d) is 15 millimeters. From this, the interference angle can be calculated:

$$\sin\theta = \frac{1 \times 8}{15} = 0.5333$$

$$\theta = 32.23^\circ$$

The students can plot different interference patterns in the same manner as in Figure A-6, using different wavelengths ($\lambda$) and distances (d). Try a plot where $d = 2 \times \lambda$ or $3 \times \lambda$. Plot the radial wave patterns carefully, and from the plot, determine the constructive interference lines and interference angles. Then calculate the interference angles using the equation, and compare the theoretical value with the plot.

Transmission Diffraction Grating—So far, we have discussed development of a spectrum using a plate with only two slits. In practice, a plate with many slits is used so that more light is transmitted through the plate, and the resulting spectrum is brighter. Such a plate is called a *transmission diffraction grating*.

Diffraction gratings are usually made by inscribing grooves or lines in a glass plate. An inscribing machine with a diamond scriber is used. The uncut glass becomes the slits in the grating. Because the spacing between the slits must be a specific number of wavelengths, the grooves must be inscribed very accurately. Therefore, a good grating is very expensive. Cheaper gratings can be obtained by making a casting from a transparent material, using a ruled glass grating as a master.

It is possible to replot Figure A-7 to illustrate the spread (dispersion) of the spectrum of visible light (Figure A-8). For this, you need some basic data such as actual wavelengths of light and typical distances between slits.

The shortest wavelength of light we can see is violet at approximately 3900 Å, and the longest is red at approximately 7600 Å. The diffraction grating used in the spectroscope whose construction is described in this booklet has 13,400 lines per inch. How many lines per millimeter does that represent? The equation is:

$$\frac{13{,}400 \text{ lines per inch}}{25.4 \text{ millimeters per inch}} = 527.559 \text{ lines per millimeter}$$

The spacing between lines (slits) is

$$\frac{1 \text{ millimeter}}{527.559 \text{ lines per millimeter}} = 0.001855 \text{ millimeter between grating lines}$$

The shortest wavelength of violet light is

$$\frac{3900 \text{ Å}}{10{,}000{,}000 \text{ Å per millimeter}} = 0.00039 \text{ millimeter}$$

and the longest wavelength of red light is

$$\frac{7600 \text{ Å}}{10{,}000{,}000 \text{ Å per millimeter}} = 0.00076 \text{ millimeter}$$

Now we can begin to calculate the interference angles for the extremes of the spectrum, using a grating with the same slit spacing as that used in the spectroscope described in this booklet.

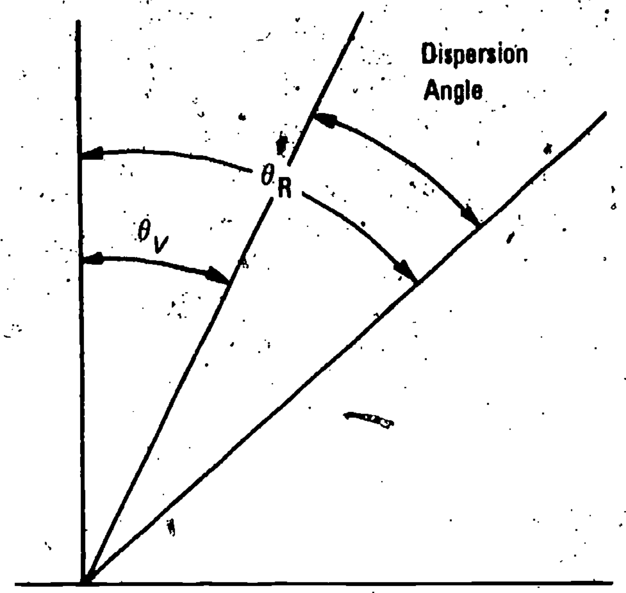



*Figure A-8 Dispersion of a Spectrum by a Diffraction Grating*

Referring to Figure A-8 again, the first-order interference angle $\theta_V$ for the violet end of the spectrum can be calculated from

$$\sin \theta_V = \frac{1 \times 0.00039}{0.001855} = 0.2102425$$

$$\theta_V = 12.14^\circ$$

and, the first-order interference angle for the red line of the spectrum can be calculated:

$$\sin \theta_R = \frac{1 \times 0.00076}{0.001855} = 0.4097035$$

$$\theta_R = 24.12^\circ$$

This gives a dispersion angle of 24.18 − 12.14 = 12.04°, which is the angle over which the spectrum is spread. These angles can be plotted on Figure A-7.

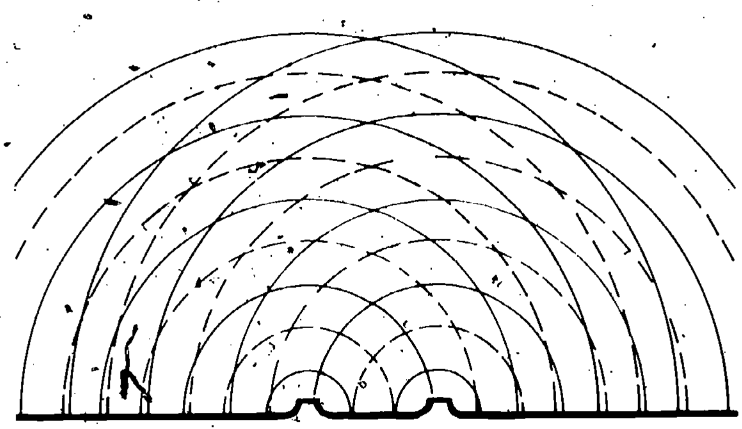
The transmission grating suffers from a limitation it shares with a prism. The limitation is that the light must be transmitted through it to develop a spectrum.

Ordinary glass cannot transmit light with wavelengths shorter than 3000 Å, which is in the ultraviolet waveband. Because the ultraviolet waveband extends from the short-wavelength end of the visible spectrum (about 3900 Å) down to less than 100 Å, it is logical to consider that ultraviolet spectra should be possible. Obviously, a glass prism or transmission grating cannot be used. A prism or grating made of calcium fluoride will transmit ultraviolet light down to a wavelength of about 1000 Å, but that still leaves an important part of the ultraviolet spectrum that cannot be reached. However, ultraviolet light can be reflected from polished metal or glass surfaces at wavelengths down to about 10Å.

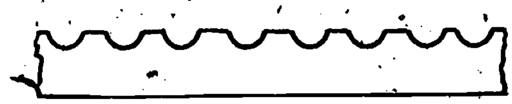
Reflection Diffraction Grating—Fortunately, the principle of diffraction works exactly the same way if the light is reflected from a series of strips of reflecting material in which the "mirrors" are the same width and have the same spacing as the slits in the transmission grating. Just as the slits in the transmission grating behave as light sources, so do the "mirrors" on what is called a *reflection diffraction grating.*

Calculation of interference angles is identical to the calculation of transmission-grating interference angles.

The relative sizes of the reflecting ridges and grooves are greatly exaggerated in the sketch below.



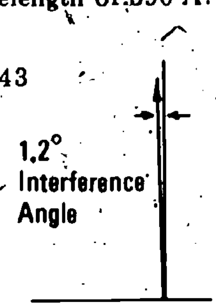
The shape of the reflection grating used in the spectroscope whose construction is described in this booklet looks more like this—enlarged, of course.



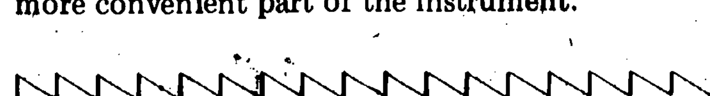
Returning to Figure A-7 and the calculation of interference angles—this time for a wavelength of 390 Å:

$$\sin \theta_{UV} = \frac{1 \times 0.000039}{0.001855} = 0.0210243$$

$$\theta_{UV} = 1.2^\circ$$




This shows that this wavelength is reflected almost back to the source of the ultraviolet light. The 1.2° angle can be changed by changing the angle of the reflecting surfaces into a configuration like a sawtooth. Now the ultraviolet spectrum will be reflected at a greater angle and produced in a more convenient part of the instrument.



Another refinement in reflective surfaces is to engrave the reflection grating on a concave surface. The result is that no lenses are required to focus the light striking the grating or focus the spectrum reflected from the grating.

In the instrument whose construction is described in this booklet, the light that enters the slit and shines on the grating strikes it at an oblique angle. This results in rotating the spectrum farther away from the perpendicular without materially changing the dispersion angle (Figure A-9).

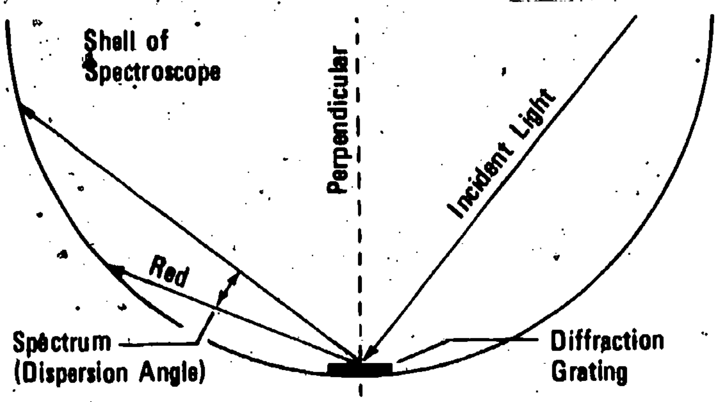


*Figure A-9 Light Path and Spectrum in Spectroscope*

Types of Spectroscopes

Spectroscopes come in many shapes and sizes. The simplest consists of a cardboard tube with a slit in one end and a piece of transmission grating in the other (Figure A-10).

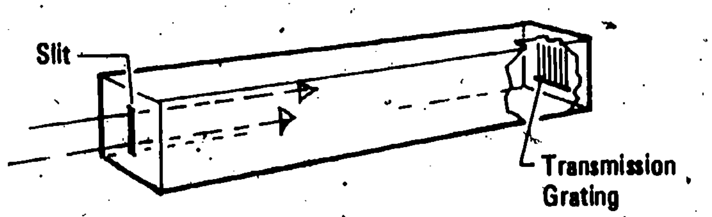


*Figure A-10 Simple Spectroscope*

A more sophisticated instrument is shown in Figure A-11. In this spectroscope, light is passed through a series of lenses onto a prism or a transmission diffraction grating. The spectrum is then studied by looking through a telescope that is pivoted so the entire spread of the spectrum can be scanned.

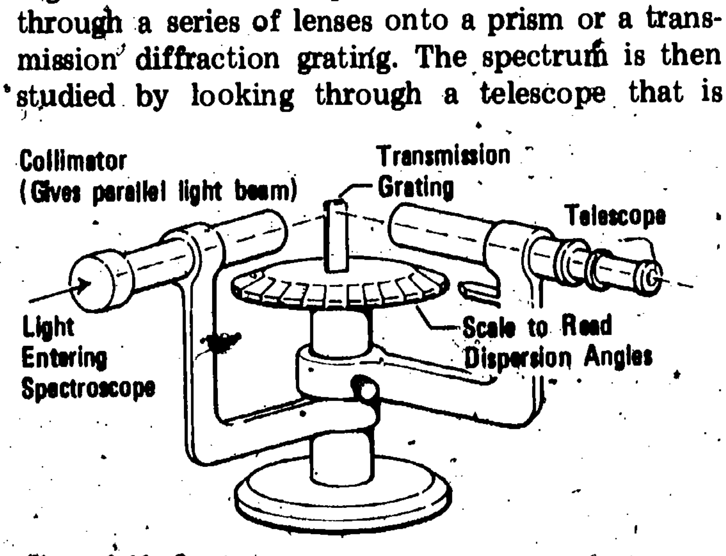


*Figure A-11 Spectroscope*

The instruments in Figures A-10 and A-11 are primarily for demonstration of the spectrum. Instruments used in operational spectroscopy are in different forms for different needs.

Dispersion of ultraviolet, visible, and infrared spectra is achieved by refraction through prisms, or diffraction by gratings. Reflection gratings have been so improved that they have become more generally used than prisms in spectroscopic instruments. The reflection grating surpasses the prism in spectral resolution and dispersion power. (Spectral resolution is the ability to separate spectral lines. The higher the resolution, the smaller is the wavelength difference between adjacent lines that can be seen. Dispersion power means the extent to which the spectrum can be spread.) These powers are practically constant across the wavelength range, whereas, in prisms, these powers vary considerably with wavelength.

In X-ray spectroscopy in the range from about 0.25 to around 15 Å, dispersion of the spectrum is achieved by reflective diffraction from a crystal. The atomic reflection planes in the crystal function as the grooves in a machined grating.

The spectroscopes used in astronomy generally represent some of the greatest advances in the development of these instruments. NASA's Skylab spacecraft carried a number of very advanced instruments for spectroscopic analysis of the Sun. Two of these are described to show the basic similarity between the simple spectroscope that can be built using this booklet and the highly sophisticated Skylab instruments.

One of these is the Ultraviolet Scanning Polychromator-Spectroheliometer. That is a cumbersome name, but it very accurately describes the function of the instrument. It senses radiation in the ultraviolet wavelength range. Because there is a need to obtain ultraviolet radiation information from the smallest possible points on the Sun, the instrument's field of view was very small. Therefore, the instrument scanned a small area on the Sun in the same way that the picture on a television screen is created by the beams of electrons sweeping back and forth across the picture tube.

*Polychromator* means that the instrument senses radiation in a number of very narrow wavebands. *Spectroheliometer* means that the instrument measures the intensity of radiation from the Sun in these wavebands.

The optical system of this spectrometer is illustrated in Figure A-12. Light from the Sun entered the instrument and shone on a concave mirror that could be rotated about two axes perpendicular to each other. The mirror reflected the light through a slit and focused it on a concave diffraction grating that dispersed an ultraviolet spectrum on a focal plane containing seven detectors placed at specific wavelength positions.

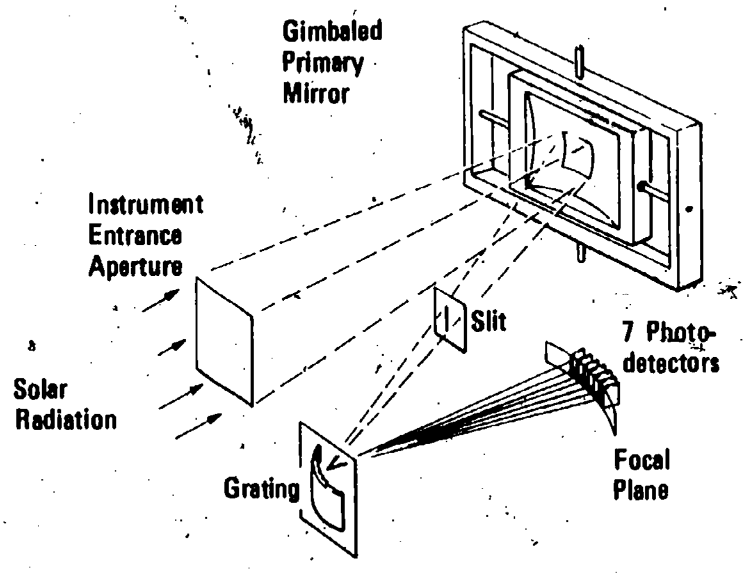



*Figure A-12 Optical System of Skylab Ultraviolet Scanning Polychromator-Spectroheliometer*

The entrance aperture of the instrument allowed radiation to enter from an area on the Sun that subtended an angle of 5 minutes at the Earth. (The whole solar disk represents an angle of about 32 minutes.) This *5-arc-minute* field of view equals an area about 22,000 kilometers square on the Sun.

The beam of radiation that passed through the slit onto the grating projected a 5-arc-second square of the Sun's surface (about 3,600 kilometers square). Movement of the mirror directed each 1/60th part of the field of view of the spectrometer onto the grating to "paint a picture" of the total scene on the Sun.

Figure A-13 is a picture of a 5-arc-minute area of the Sun. The picture has 60 horizontal lines, each 5 arc seconds high. Each line is divided into 120 rectangles that result from the 50% overlap of the 5-arc-second squares defined by the size of the instrument's slit.

*Figure A-13*

*Ultraviolet photograph of 2,7 billion square kilometers of the Sun. The curved shapes show magnetic field lines in the highly energized atmosphere about 100,000 kilometers above the Sun's surface.*

Another Skylab spectrometer was called a spectroheliograph. Its function was to develop ultraviolet spectra of the Sun. The optical system of this instrument is shown in Figure A-14.

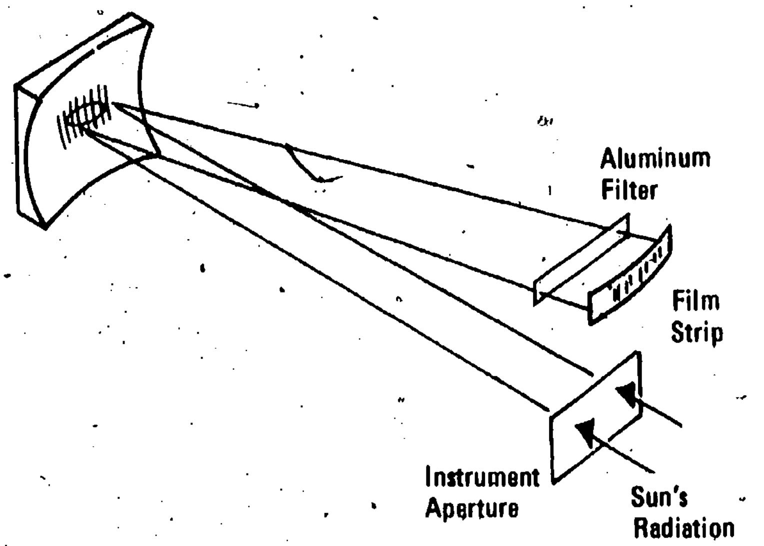



*Figure A-14 Spectroheliograph Optical System*

A notable difference between this instrument and the spectroheliometer, and the instrument that can be built using the instruction in this booklet, is that there is no slit through which the sunlight could pass before reaching the grating. Instead, radiation from the entire solar disk fell on the grating and was dispersed.

The spectrum recorded at the focal plane showed an image of the solar disk centered on each emission wavelength. The brightness of the image indicated the intensity of solar radiation at each wavelength. Figure A-15 shows part of one of the films taken by this instrument. The very bright image shows how the Sun "appeared" in the ultraviolet wavelength of 304 Å.

Most of the Sun's disk is visible, with a pattern of lighter and darker areas. These represent areas of greater and less activity on the Sun. To the left of the 304-Å image, you can see other faint images, one of which is outlined by a dashed line. This image was obtained at a wavelength of 284 Å. Except for a relatively few small areas, the intensity of the radiation at this wavelength was much lower than the 304-Å radiation. The bright areas on the 284-Å image can easily be matched with the brightest areas on the 304-Å image, showing that they are caused by the same phenomenon on the Sun.

Also visible in the 304-Å image is a massive prominence where matter has been ejected from the Sun to reach an altitude of about 600,000 kilometers from the surface. It is noticeable that this material is not discernible in the 284-Å image, although there is evidence of high-energy activity at the base of the prominence.


Iron$^{+14}$ (284 Å) Helium$^{+}$ (304 Å)

*Figure A-15 Ultraviolet Spectroheliogram*

## Summary

The simple spectroscope that can be built by following the instructions in this booklet, crude though it may appear, is basically the same type of instrument that has many applications in various scientific disciplines. The difference between this and other instruments lies primarily in the quality of manufacture; and quality is what causes the difference in cost.

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