In the last chapter we saw how water waves demonstrate an interference pattern when waves from two-point sources intersect each other. In this chapter we will find that we can see an interference pattern with light just as we saw with our water wave model. This final analogy between light and water waves enables us to say with some confidence that light behaves like a wave, since just about all the features we have found in water waves we have also found with light.

This wave model for light is an excellent example of the method by which scientific knowledge advances. First, a phenomenon (light in our case) is studied in detail, as we did in chapters 17, 18 and 19. Then a model, such as the wave model for light, is developed to enhance our understanding of the phenomenon. To see if the model is valid, the predictions of this model are compared to the actual behavior of the phenomenon, as we did when we tried to see if the wave model accounts for reflection and refraction. If the model survives to that point, we then asked if the model predicts any properties of the phenomenon not yet actually observed. In our case, the wave model predicts the phenomenon of interference, and we did observe interference patterns with light when we looked for them carefully. In this way, an approach to science using models can help answer fundamental questions about a phenomenon and can lead to new discoveries about the phenomenon.

Having made you content with your understanding of light behavior, we will now throw in a monkey wrench. (If we don't, we would be dishonest.) Until the beginning of this century, physicists too were satisfied with the wave description of light. But about this time several experimental physicists, investigating the effects light has on matter, obtained results that could not be understood using only the theory of waves. We will look at some of these experiments and see that the wave theory of light, while not wrong, doesn't tell the whole story. Under certain circumstances it will be more satisfactory to think of light as coming in discrete packages called photons. We will also see that these photons behave, in some circumstances, like familiar particles.

It will be worthwhile for us to become comfortable with the "Jekyll and Hyde" nature of light. Evidence from other experiments designed to investigate the nature of the atom and its parts also supported the duality of light. And....when you are asked to learn that particles composing matter behave at times like waves....you will not be too surprised.

PERFORMANCE OBJECTIVES

After completing this chapter, you should be able to:

1. Set up an experiment which shows that the wavelength of red light is greater than the wavelength of blue light and using experimental data, calculate the wavelength of each.

2. List the factors that affect:
   a. a double-slit interference pattern,
   b. s single-slit diffraction pattern.

   And be able to discuss verbally how each factor affects the pattern.

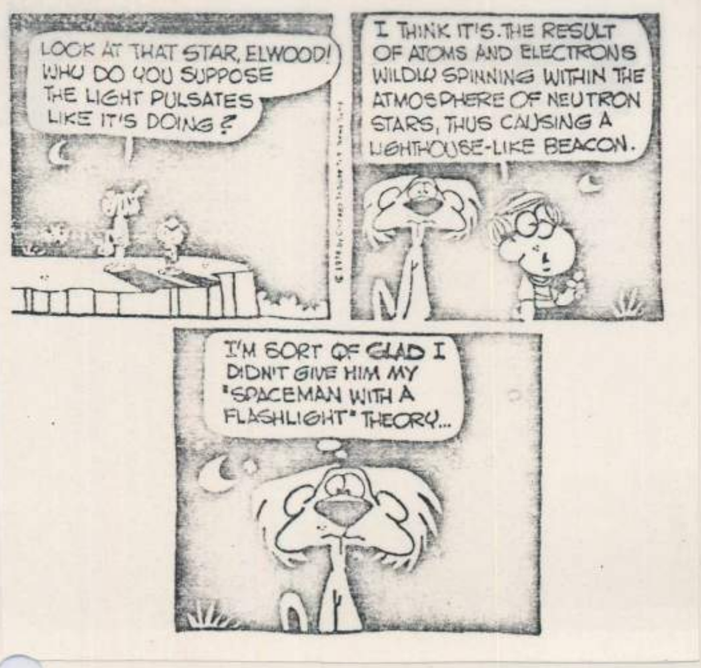
3. Experimentally determine the wavelength of a laser using a double-slit interference pattern.

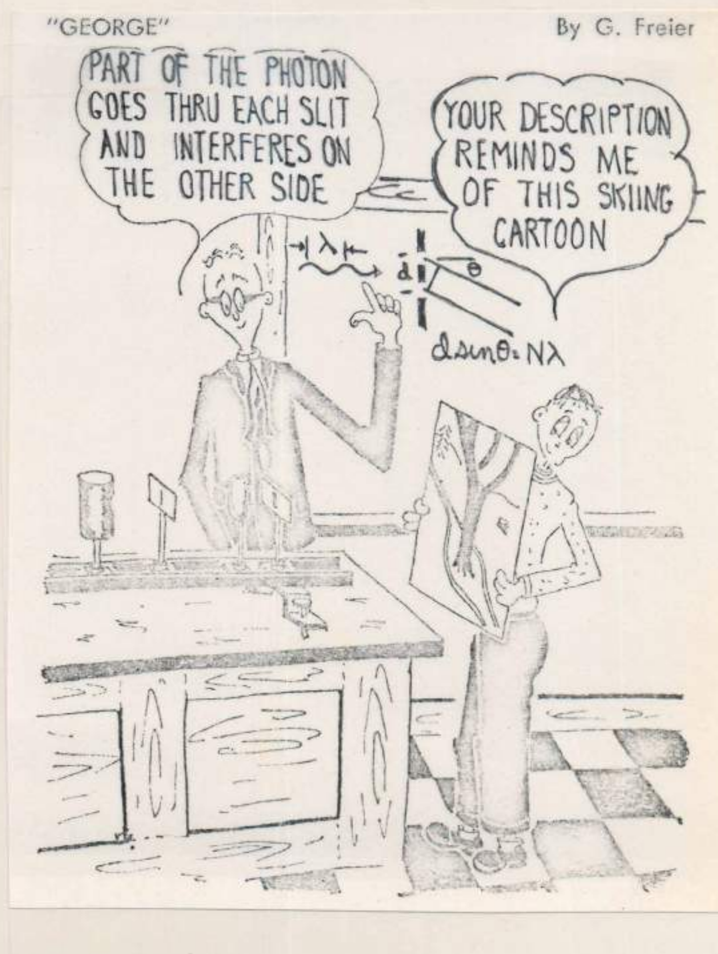
4. Predict the number of anti-nodal lines and their location which are produced using a many line "diffraction" grating.

5. Verbally:
   a. contrast how the wave and particle model predicts the transfer of energy from one point to another, and
   b. describe the experimental evidence that shows that light comes in packets of energy called photons.

6. Use the ideas of Planck which showed that the energy of the photon ($E = h\nu$) could be used to explain the photoelectric effect.

7. Calculate mathematically the energy, momentum and wavelength of a photon.





1. Read: Section 25-1 Observing Interference in Light: Young's Experiment page 503
   25-2 Color and the Wavelength of Light page 505

   a. What factors must you consider if you are designing an experiment to show an interference pattern with light?

   b. What does the angle of any nodal line depend on?

   c. Explain to you instructor the origin of the equation: $\Delta x = L\lambda/d$.

   d. What assumptions must you not forget when you use the equation?

2. Problems: page 505: #1 #2

3. Obtain: Single-filament clear lamp, socket, colored filters and Cornell-Slitfilm Demonstrator (Instructions provided.)

   a. Read the section opposite the schematic diagram on the instruction sheet.

      1. The top digit refers to ________________________________.

      2. The middle digit refers to ________________________________.

      3. The bottom digit refers to ________________________________.

      4. The number under the pattern refers to ____________________.

   b. View the lamp through the top element of the 4th column. Describe and sketch the single slit diffraction pattern.

   c. View the lamp through the 2nd element of the 4th column. Contrast this pattern with that seen in 'b'. Sketch this double slit interference pattern.

   d. Using the one double slit in the 4th column and the 4 double slits in the 5th (right) column:

      1. Investigate the interference patterns.

      2. What variable(s) are changing? How does the affect the pattern?

   e. Cover up the bottom half of the lamp with a blue filter and the top half with a red filter. Reinvestigate that which you did in (b), (c) and (d).

   f. Optional...Film Loop L-2 DOUBLE SLIT is available for viewing.

4. Determine the wavelength of both the red and blue light using one of the double slits of the Slitfilm Demonstrator. Experiment 42 YOUNG'S EXPERIMENT page 91 may be of help. Report to your instructor the following data for each color:

   d, Δx, L, λ, % error

5. Calculate the wavelength of the light from the laser using one of the double slits. Results?

   Note..Have instructor set up the laser and brief you on its safe use.

6. Problems: page 507: #3 #4 #5
   525: #28 #29 #30

7. Read: Section 25-3 Diffraction: An Interference Effect.... page 508

8. The left column of the Slitfilm Demonstrator contains 5 single slits which become narrower as you go down the column.

   a. How does the size of the slit affect the diffraction pattern?

   b. How does the diffraction pattern of the first slit in column 4 compare to that of the lowest one in the left column?

   c. You might wish to view the Film Loop: L-1 SINGLE SLIT.

9. Read: Section 25-4 A theory of Diffraction by a Single Slit page 510

10. Optional...Ask instructor for special demonstration which might lend support to the theory of the single slit.

11. Using the Slitfilm Demonstrator, complete the following:

    a. Observe the single filament light source using the 5 elements in the 4th column. What variable is changing as you go down the column?

    b. How does this affect the resulting pattern?

    c. Observe the single filament light source using the lower three elements in the center column. What variable(s) change as one goes from bottom up?

    d. How does the change affect the resulting pattern?

12. Calculate the number of "anti-nodal" lines and their location (in degrees) using a monochromatic light source of 6328 Angstroms when using a replica grating of:

    a. 300 lines per mm　　b. 600 lines per mm

    After reporting your findings to your instructor, ask to check your results using the appropriate replica gratings and light source.

13. Look at the eye chart on the wall in the front of the room with the various single slits of the Slitfilm Demonstrator. What affect does the following have on ones ability to resolve the letters on the chart.

    a. Changing the size of the slit when viewing the chart from one position.

    b. Changing the distance from the chart while looking through one slit.

c. Changing the color of the filter (red and blue) as one looks through one slit at a fixed distance.

14. Problems: page 512: #8 #9 #10

15. Read: Section 25-5 Experimental Checks with Single and Double Slits page 512.

16. Obtain a metal rectangular loop suspended in a graduate cylinder which contains a soap-glycerin-water solution. Dip the loop in the soap solution and pull it upward until it is out of the solution. Suspend it using the clip provided.

    a. View the film using reflected colored light using filters provided.

    b. View the film through the filters using transmitted colored light.

    c. Also view the film under reflected and transmitted white light.

17. Obtain a Newton Rings Apparatus.

    a. Observe the interference pattern when light is reflected from an air film between a spherical glass surface and a plane surface that are in contact near the center. What is observed at the point of contact?

    b. Next observe the interference pattern when light is transmitted through the apparatus. How does this pattern compare to the one observed by reflected light?

    c. Make sketches of the two observations for instructor approval.

18. Write a brief summary indicating the theory behind interference due to reflection from thin films. To save time you might outline your thoughts.

    Note...See Study Notes 1: Transmission of Non-Reflective Coatings.

19. Problems: page 513: #11 #12 #13 #14

20. Read: Section 25-6 Electromagnetic Waves & Electromagnetic Spectrum page 513

21. Film: ELECTROMAGNETIC WAVES 32 min (Film notes provided.)

22. Film: PHOTONS 18 min (Film notes provided.)

23. Read: Section 25-7 Difficulties with the Wave Model page 515

    a. What does the wave picture of light predict about the ejection of electrons from matter?

    b. What experimental evidence was observed relative to the ejection of electrons from matter?

    c. What is a possible explanation?

d. A bundle of light is called a _________.

e. Popping corn demonstrates wave or particle theory of how light transfers energy?

24. Problems: page 517: #17 #18

25. Film: PHOTOELECTRIC EFFECT 28 min (Film notes provided.)

26. Read: Section 25-8 The Synthesis: Einstein's Interpretation of the Photoelectric Effect page 517

a. When mono-energetic photons hit a metallic plate, where does the energy of the photons go?

b. Mathematically: $E_{photon} = \theta + E_{K\ (electron)}$
θ represents ___________________________________.

c. When would no electron be ejected?

d. What is the mathematical relationship between the energy of a photon and its:

1. frequency? 2. wavelength?

e. "h" is called Planck's constant and has a value of:
____

f. Obtain Transparency T-37 PHOTOELECTRIC EQUATION.

Use it to explain to your instructor the implications of the photoelectric effect.

g. $E = hc/\lambda$ = ______________________ e.v. - $\mathring{A}/\lambda$.

27. Problems: page 520: #19 #20 #21 #22 #23

28. Read: Section 25-9 Graininess And Interference: A New Kinematics page 521

a. When photons produce an interference pattern:

1. Do they interfere with each other?

2. Is it due to individual photons?

3. What evidence supports the idea that interference is due to individual photons?

b. How does an individual photon interfere with itself?

c. If we do not know, then where do we go from here?

d. Refer to Study Notes titled: WAVE-PARTICLE.

29. Problems: page 522: #25 #26 #27

30. Read: Section 25-10 Photons and Electromagnetic Waves page 523

a. How is the wave and particle model of light combined?

1. If the wavelength of a photon is large, what can we conclude about the energy of the photon?

a. If the wavelength of a photon is 300 meters, its energy is ____________________e.v.

b. Can we detect this amount of energy?

c. If not, then what do we observe?

d. Which model describes this?

2. If the wavelength of a photon is small, what can we conclude about the energy of the photon?

a. Can we detect individual events do to one photon?

b. As the wavelength decreases, what happens to our ability to show interference and diffraction?

c. Which model describes this?

31. Summary

a. Light sometimes behaves like waves, sometimes like particles (photons).

b. Why? It just does. (We do not know why.)

c. We can only learn that it exists, how it behaves and then be able to predict what will happen.

d. Classical Physics - (for particles that are moving slow)

The energy and momentum are used to predict where particles will hit, or where they will be at a given time.

e. Quantum Physics - (for photons)

The energy and momentum are used only to assign probabilities where photons will hit predicted by the wave theory.

32. Complete the enclosed Written Exercise and then have it evaluated.

1. (a) Must have slit width less than or equal to the wavelength.
   Need sources in phase or light through both openings in phase.
   (b) the wavelength and the distance between slits
   (c) Its origin was from one of the equations developed in chapter 24.
   (d) for L to be the same or nearly so, x must be small

2. (1) There would be no interference pattern. S.A.B.
   (2) The spacing between alternate light and dark bars would be:
   (a) greater (b) closer

3. (b) Here we see a SINGLE SLIT DIFFRACTION pattern.
   (c) Here we see a DOUBLE SLIT INTERFERENCE pattern.
   The single slit diffraction pattern is there too.
   (d) (2) only 'd'

6. (3) 0.68 mm
   (4) further apart
   (5) (a) 3 red and 4 blue (b) 3/4
   (28) 1.5 m, 0.7cm
   (29) (30) S.A.B.

8. (a) smaller slit width 'w' implies broader diffraction pattern

11. (a) more slits (only)
   (b) Intensity of anti-nodal lines increase
   width of bright lines decrease
   (c) more slits, 'd' decreases, 'w' decreases
   (d) x increases, lines brighter but narrower

12. (a) $n = 5$, $\theta_1 = 10.9$, $\theta_2 = 22.3$, $\theta_3 = 34.7$, $\theta_4 = 49.4$, $\theta_5 = 71.6$
   (b) $n = 2$, $\theta_1 = 22.3$, $\theta_2 = 49.4$

13. (a) better resolution with greater slit width
   (b) better resolution when closer
   (c) better resolution when viewed with a shorter wavelength (blue)

14. (8) (10) S.A.B.
   (9) (a) 0.033°, 0.066°, 0.100° (b) 0.0033°, 0.0066°, 0.0100°
   (c) 0.33°, 0.66°, 1.00°

19. (11) (13) S.A.B
   (12) Increase slit separation keeping slit width constant.
   (14) (a) 6 (b) 0.4

23. (a) Energy being transferred as a continuous process. Thus there would be ejection of electrons at regular intervals with a time delay at the beginning.
   (b) Electrons ejected randomly, some with no time delay.
   (c) Light carries energy in hunks (packets) as particles do.
   (d) photons (e) wave

:4. (17) (18) S.A.B.

26. (a) It is given to an electron of one of the atoms.
    (b) Binding Energy
    (c) When energy of the photon is less than the binding energy.
    (d) (1) $E = h\nu$ (2) $E = hc/\lambda$
    (e) 6.626×10^{-34} Joule-sec or 4.136×10^{-15} e.v.
    (g) 12400

27. (19) 7.4×10^{14} Hertz
    (20) 2 eV
    (21) S.A.B.
    (22) (a) 4.6×10^{14} Hz (b) 3.0×10^{-19} J (c) 1.9 eV (d) 1.8 eV, 3.1 eV
    (23) 0.5 volt

28. (a) (1) no (2) yes (3) Taylor's Experiment
    (b) We don't know - maybe it doesn't.
    (c) need something new, maybe...a new theory

29. (25) 210 eV/sec
    (26) (a) 4.0×10^{-19} Joule (b) 8×10^{-7} sec (c) 240 meters (d) 200 times
    (27) S.A.B.

30. (a)(1) energy is small
    (a)(1)(a) 4×10^{-9} e.v. or 6.6×10^{-28} Joule
        (b) no, nor can any known apparatus
        (c) only average effects
        (d) wave model
      (2) energy is larger for smaller wavelength
        (a) In many instances yes, particularly as wavelength gets smaller
        (b) It becomes harder to show.
        (c) particle model

1. Read: Section 25-1 Observing Interference in Light: Young's Experiment page 503
   25-2 Color and the Wavelength of Light page 505

   a. What factors must you consider if you are designing an experiment to show an interference pattern with light? $d/\lambda < 1$ in phase

   b. What does the angle of any nodal line depend on? λ, d

   c. Explain to you instructor the origin of the equation: $\Delta x = L\lambda/d$.

   d. What assumptions must you not forget when you use the equation? Δx small

2. Problems: page 505: #1 #2

3. Obtain: Single-filament clear lamp, socket, colored filters and Cornell-Slitfilm Demonstrator (Instructions provided.)

   a. Read the section opposite the schematic diagram on the instruction sheet. 1 POINT = 0.013837 inch

      1. The top digit refers to # of lines in element.

      2. The middle digit refers to WIDTH OF ELEMENT.

      3. The bottom digit refers to SPACING BETWEEN LINES.

      4. The number under the pattern refers to DISTANCE IN (MM) BETWEEN LINES.

   b. View the lamp through the top element of the 4th column. Describe and sketch the single slit diffraction pattern.

   c. View the lamp through the 2nd element of the 4th column. Contrast this pattern with that seen in 'b'. Sketch this double slit interference pattern.

   d. Using the one double slit in the 4th column and the 4 double slits in the 5th (right) column:

      1. Investigate the interference patterns.

      2. What variable(s) are changing? How does the affect the pattern?

   e. Cover up the bottom half of the lamp with a blue filter and the top half with a red filter. Reinvestigate that which you did in (b), (c) and (d).

   f. Optional...Film Loop L-2 DOUBLE SLIT is available for viewing. FILM LOOP

4. Determine the wavelength of both the red and blue light using one of the double slits of the Slitfilm Demonstrator. Experiment 42 YOUNG'S EXPERIMENT page 91 may be of help. Report to your instructor the following data for each color:

   d, Δx, L, λ, % error

d. A bundle of light is called a _________.

e. Popping corn demonstrates wave or particle theory of how light transfers energy?

24. Problems: page 517: #17 #18

—1855

25. Film: PHOTOELECTRIC EFFECT 28 min (Film notes provided.)

26. Read: Section 25-8 The Synthesis: Einstein's Interpretation of the Photoelectric Effect page 517

2318

a. When mono-energetic photons hit a metallic plate, where does the energy of the photons go?

b. Mathematically: $E_{photon} = \beta + E_{K\ (electron)}$
β represents ___________________________________.

c. When would no electron be ejected?

d. What is the mathematical relationship between the energy of a photon and its:

1. frequency? 2. wavelength?

e. "h" is called Planck's constant and has a value of:

____

f. Obtain Transparency T-37 PHOTOELECTRIC EQUATION.

Use it to explain to your instructor the implications of the photoelectric effect.

$= 1.24 \times 10^3\ eV \cdot nm$

Change g. $E = hc/\lambda$ = 1.24×10^4 e.V. - Å/λ.

27. Problems: page 520: #19 #20 #21 #22 #23

28. Read: Section 25-9 Graininess And Interference: A New Kinematics page 521

Video Interfering photons Beginning Tape

a. When photons produce an interference pattern:

1. Do they interfere with each other?

2. Is it due to individual photons?

3. What evidence supports the idea that interference is due to individual photons?

b. How does an individual photon interfere with itself?

c. If we do not know, then where do we go from here?

d. Refer to Study Notes titled: WAVE-PARTICLE.

29. Problems: page 522: #25 #26 #27

Cornell

INTERFERENCE and DIFFRACTION

Slitfilm Demonstrator

DIRECTIONS FOR USING

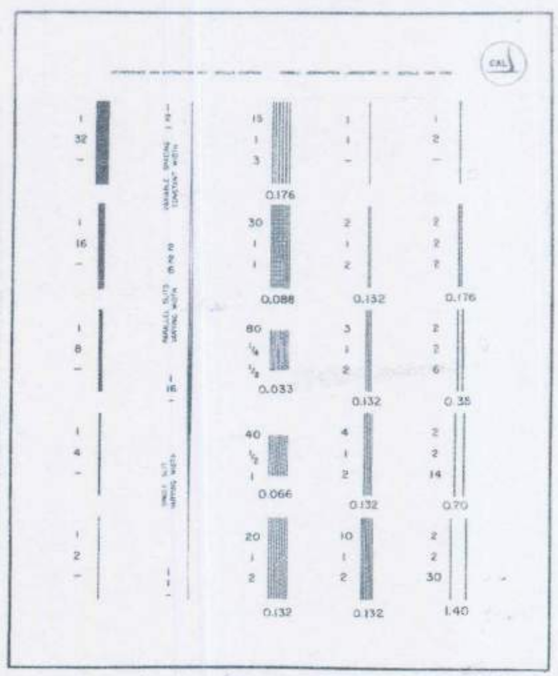
in demonstration of the phenomena
of interference and diffraction effects
in physical optics.

MANUFACTURED AND SOLD BY
THE NATIONAL PRESS
PALO ALTO, CALIFORNIA

PROPERTIES REQUIRED FOR THE DEMONSTRATION

For best results in demonstration of interference and diffraction, each student should have a slitfilm for his personal use during lecture discussions. Equally usable is the glass-bound slitfilm, or the film itself unbound, although the latter, subject to surface scratching, is likely to become less effective upon the diffusion of light through a scratched surface.

For viewing the phenomena through the slitfilm,* one requires a clear glass single-filament lamp, such as Type T-10 120-volt clear showcase lamp, 1¼" in diameter, 5⅞" long, available in any electric or hardware store for about 29c, or for large classes, a tubular clear glass showcase lamp, Type 40-T8, 40 watts, 120 volts, 12" long, approximately $1.20.



Schematic arrangement of single slits, double slits, multiple slits, etc. on the viewing slide. Beside each element, the top digit refers to the number of lines in the element in the finished slide, the middle digit to the width in points of the elements before the 8X reduction and the bottom digit to the spacing in points between lines. (One point is 0.013837 inch, a measure commonly used by printers, which was the basis for the original chart.) The distance in millimeters between the centers of the slits is shown under the patterns. This distance is approximate since film shrinks slightly with age. As indicated above, this figure is schematic only; for instance, the pattern having 15 lines in the slide has only six in this drawing.

DIRECTIONS FOR USING THE CORNELL INTERFERENCE AND DIFFRACTION SLITFILM

1. Set the lamp with the filament *vertical* at any convenient distance from the observer, from one foot to fifty feet. A single lamp is sufficient for a whole class.

2. Hold the slide with the long dimension *vertical*, with the Cornell Aeronautical Laboratory monogram (monogram) in the *upper right* corner, as illustrated on the chart.

3. Hold the film *close to the eye* (almost touching the eye) and *look through the slide at the single-filament lamp.*

4. More than twenty different patterns may be seen by looking through the different elements on the slide. For example, on the left is a column of single slits of different widths. The slit at the top is so wide that things will appear quite normal when seen through it. As one goes down the column, the slits get narrower, and the single-slit diffraction pattern gets broader. (The filament becomes less distinct and "broader.")

On the right, except for the top element which is a single slit, there is a column of double slits of different spacings. The farther apart the slits, the closer together are the interference fringes of the double-slit interference pattern.

In the fourth column is a group of multiple slits; secondary maxima can be seen in at least two of the patterns.

In the middle column is a group of coarse diffraction gratings having various ratios of slit widths to slit spacings.

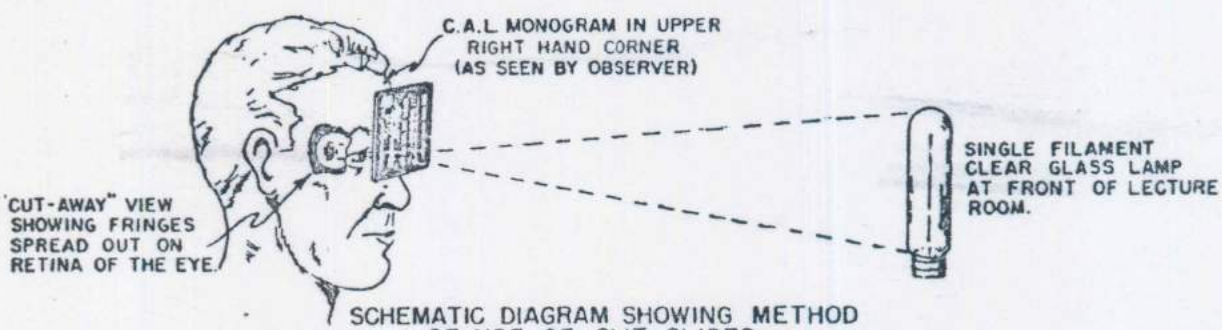
The pattern in the center of the slide gives the greatest dispersion. With this pattern coarse measurements may be made of the wavelength of the green mercury line in an ordinary fluorescent lamp, (covered by a narrow slit), or of the most prominent neon lines in a neon lamp, etc. The second "column" shows a double slit of variable spacing but constant width, faired into a double slit of constant spacing but varying width, faired into a single slit of varying width. When this pattern is drawn past the eye (vertically), many phenomena can be seen.

5. Many additional phenomena can be demonstrated. One may use blue and red color filters over the lamp, from which it will be seen that the patterns are wider with the longer wavelength red light. One may observe the position of "missing orders," although in the closely spaced patterns, it is not possible to control missing orders too well. If one looks at a pattern of closely spaced sources (for example, a transparent line source with lines spaced about ¼ inch apart), then many interesting phenomena can be seen. Tilting the slide about a vertical axis in effect varies the slit spacing. In respect to directional characteristics, it is desirable to draw analogies among optics, sonar, and radars, etc.

6. It is worth noting why the filament of the lamp appears to be spread out in a series of fringes. Actually, the filament is not altered when the slit is put in front of the eye, but the slits produce interference or diffraction patterns focussed and *spread out on the retina* of the eye. Because the pattern is spread out on the retina, we "see" the pattern spread out in space.

7. For further information on the slitfilm, see Seville Chapman and Harold Meese, *American Journal of Physics*, 25, 135-138, March 1957. For further information on the phenomena to be observed, consult any good book on physical optics (for example, Jenkins and White), and study the chapters on interference and diffraction.

Additional slitfilms may be obtained from The National Press, Palo Alto, California.

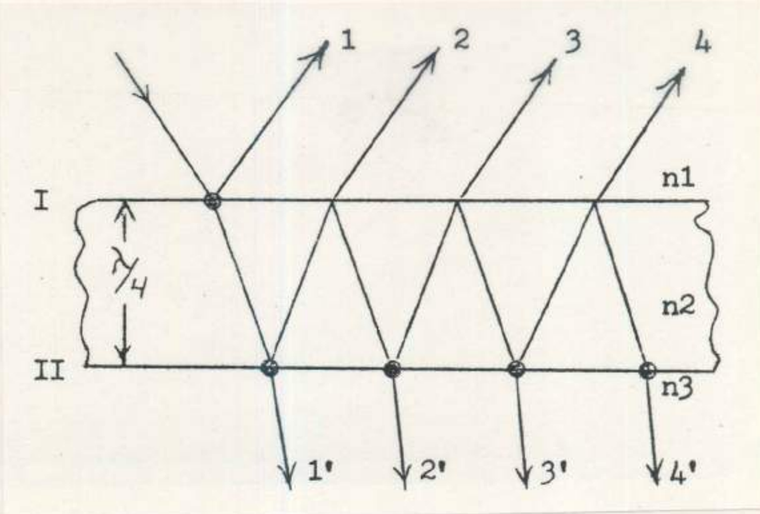


SCHEMATIC DIAGRAM SHOWING METHOD OF USE OF SLIT-SLIDES.

TRANSMISSION BY NON-REFLECTIVE COATINGS - Mario Iona - University of Denver

Belief in the principle of conservation of energy ought to be sufficiently persuasive to argue that the transmitted beam must be enhanced whenever reflections are repressed by the coating. Thus, the transmitted beam will contain the full intensity of the incident beam if absorption can be neglected.

Many arguments described only one beam reflected from the second surface, but for a realistic analysis, we must take multiple reflections into account. Referring to the diagram, one can see that there are a large number of reflected beams with successively decreasing intensity as light is transmitted at each reflection.



Although the diagram shows an incident beam which is not normal to the surface, the discussion deals only with the simpler case of normal incidence.

The refractive indices of the three materials are of increasing magnitude, $n3 > n2 > n1$. Heavy dots indicate surfaces of greater refractive index where reflected waves suffer a phase shift of 180^{o} equivalent to half a wavelength. Reflected beams 1 and 2 will be out of phase and, therefore, interfere destructively because both suffer a reflection phase shift but beam 2 travels an extra half wavelength.
Similarly, beams 1 and 3, as well as 1 and 4 interfere. If the materials are chosen so that $(n2)^2 = n1 \times n3$, the amplitude of reflected wave 1 will be exactly equal to the combined amplitudes of the other waves coming back from surface I and complete destructive interference will occur.

On the other hand, using similar logic, it can be shown that transmitted beams 1′ and 2′ will interfere constructively because beam 2′ suffers a phase reversal and travels a half wavelength more than beam 1′. Similarly, beams 3′ and 4′ also interfere constructively with beam 1′.

The transmitted beam will, therefore, show a maximum of intensity when the coating thickness is one fourth the wavelength.

If the thickness is not chosen properly to give a non-reflective coating (of one fourth wavelength), not only will the reflected waves fail to cancel each other completely, but the transmitted waves will not add to their possible maximum so that the transmitted intensity is reduced.

TEACHER'S GUIDE TO THE PSSC FILM

ELECTROMAGNETIC WAVES (33 min.)

George Wolga, M.I.T.

The aim of this film is to display the common behavior of electromagnetic radiation over a wide range of wave lengths.

The film should be shown with Section of the PSSC text.

Summary:

Professor Wolga states the properties common to the different regions of the electromagnetic spectrum; electromagnetic radiation originates from accelerated charges and can be described as a transverse polarizable wave traveling with the speed of light.

To demonstrate that visible light can be generated by the acceleration of charges, he shows us the light radiated by high energy electrons in a synchrotron as they are forced to move in a circular path.

Professor Wolga then performs a series of experiments to show some wave properties in four different regions of the spectrum.

First, in the region of visible light, he demonstrates a double-slit interference pattern and shows that light can be polarized. Then in the X-ray region he measures, with a geiger counter, the intensity of X rays reflected from a crystal lattice. The intensity exhibits the maxima and minima characteristic of an interference pattern.

In the microwave region, the interference pattern of radiation from two microwave sources is demonstrated. The polarization of these microwaves is also shown.

Finally, the interference pattern formed by radio waves sent out from two antennas is sampled by moving a receiving antenna through the resulting electric field. The polarization of the radio waves is shown.

These experiments indicate the unity of the electromagnetic spectrum.

Points for Discussion and Amplification:

(a) Because of the difficulty of the necessary experiments, the transverse nature and polarizability of X rays were not exhibited. These features have been established (e.g. by scattering experiments) for X rays and for waves of even shorter wave length.

(b) For a more descriptive discussion of the generation of an interference pattern by wave reflection from a crystal lattice see the PSSC text, Fig. 33-14.

(c) The deceleration of the electrons in an X-ray tube, as they strike the anode, produces a spectrum with a continuous distribution of wave lengths. Because of this, the student may find it difficult to understand how interference maxima could be observed at various angles rather than a smoothly varying counting rate. The point

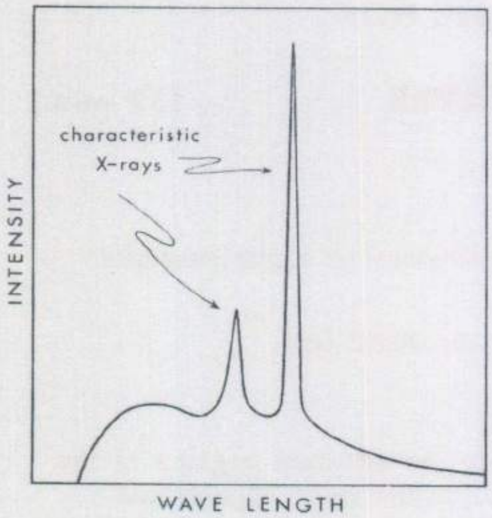


Fig. 1. A typical X-ray spectrum. Note that there is a minimum wave length. This wave length is related to the kinetic energy of the bombarding electrons.

should be emphasized that it was not this continuous distribution of X rays that was being counted, but rather it was principally the X rays which are characteristic of the electron motion in the atoms of the anode materials. (Fig. 1). These characteristic X rays come in a few discrete wave lengths (spectral lines) and are much more intense than the continuous X rays from the deceleration of the bombarding electrons.

At the energies used with the X-ray tube in the film, the bombarding electrons lose most of their energy by exciting the atoms of the anode material producing the characteristic X rays.

(d) In order to make the microwave and radio-frequency signals activate a loud-speaker they were "chopped," that is, the signals are turned on and off with the frequency heard on the loud-speaker.

(e) If you use the PSSC film, Sound Waves in Air, remind the students that the techniques used there to show that sound was a wave phenomenon are the same as those in this film.

(f) To clarify the film discussion on polarized light, consider the diagram in Fig. 2.

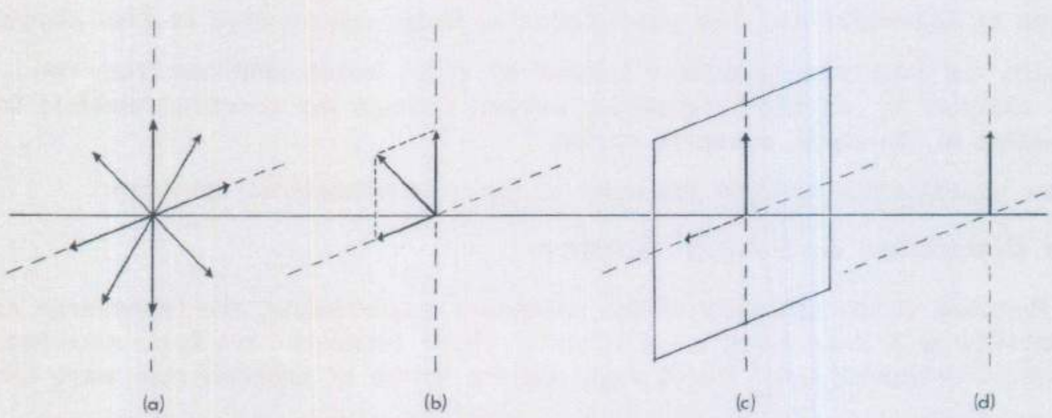


Fig. 2.

Because electromagnetic radiation has the properties of transverse waves, its electric field can vibrate in all directions perpendicular to the direction of propagation. This is shown schematically in (a) of the figure. Each of the electric fields along the direction shown at (a) can be separated into vertical and horizontal components. One of the possible electric fields is shown at (b) along with its components. The polarizing material at (c) allows only the vertical components of the electric fields to pass. At (d) the light is polarized: the electric field oscillates only along the vertical direction.

In the microwave and radio-wave experiments in the film, the wave was polar-

TEACHER'S GUIDE TO THE PSSC FILM

PHOTONS (19 min.)

John King, M.I.T.

In this film an experiment is performed to demonstrate the particle nature of light. The film relates to Section of the PSSC text.

Summary:

Professor King describes the apparatus he will use to demonstrate that light exhibits a particle-like behavior. A photomultiplier detects the very weak light used in the experiment. The operation of this device is outlined and the amplification is determined to be about 10^6 by measuring the output current and photoelectron current going into the first stage of the photomultiplier. The photomultiplier is connected to an oscilloscope, and pulses are seen on the oscilloscope trace. He shows that the pulses are due to the weak light shining on the photomultiplier, but that some pulses are due to background noise. To reduce this thermal background, the photomultiplier is cooled by a mixture of Dry Ice and alcohol.

The difference between the continuous wave model and the particle (photon) model for the transport of light energy is illustrated by an analogy to the delivery of milk. He shows that if the milk is to be delivered at the rate of one quart every ten seconds this can be achieved in either of two ways: (1) a pipe in which milk flows continuously at the uniform rate of one quart every ten seconds, or (2) a conveyor belt on which quart cartons of milk are randomly positioned so that on the average one quart of milk is delivered every ten seconds.

In the first case then, there is a consistent 10-second delay before one quart of milk is delivered. However, in the second case, although on the average one quart (packaged) arrives every ten seconds, there is no consistent delay between the arrival of successive quarts; and thus some arrive at intervals of less than 10 seconds. It is this idea, of looking for the arrival of packages in less than the average time interval, that Professor King uses to find out whether light energy comes in packages (photons).

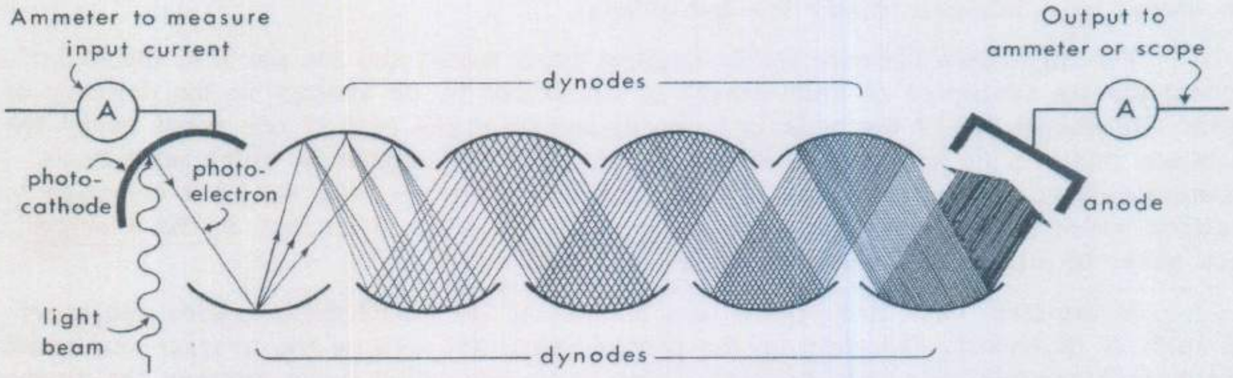
A beam of light shines on the photomultiplier through a hole in a disc. The light intensity is reduced with filters until the output current of the photomultiplier is only 3×10^{-10} amperes, implying that the photoelectron current is 3×10^{-16} amperes. This is equivalent to an average of one electron from the photocathode every $\frac{1}{2000}$ of a second. The photomultiplier output is displayed on the oscilloscope and, with the disc spinning at a constant rate, it is determined that the light shines on the photomultiplier for $\frac{1}{5000}$ of a second during each revolution. From the analogy using the flow of milk it is argued that a continuous transport of light energy would require $\frac{1}{2000}$ of a second between pulses from a photoelectron; whereas a particle model would imply that at any instant during the $\frac{1}{5000}$-second interval one might see a pulse from a photoelectron, with the average rate still one pulse every $\frac{1}{2000}$ of a second. The pulses are seen to arrive randomly during the $\frac{1}{5000}$-second interval implying the particle nature of light.

Points for Discussion and Amplification:

(a) As performed in the film, the experiment demonstrates that pulses due to photoelectrons arrive at the oscilloscope at random times. From this it is inferred that light comes in packages. But this conclusion is based on additional experimentation and argument which is not done in this film. Such experiments include a consideration of the efficiency of the cathode in the photomultiplier and the mechanism of the absorption of the light at the cathode leading to the ejection of photoelectrons. These and other experiments have been performed (e.g., photoelectric effect) which conclusively demonstrate the particle nature of light energy.

(b) Students may wonder whether the pulse measured at six microseconds after the start of the light flash is a photoelectron or a thermal electron (background noise) and rightly so, since the one event shown is statistically insignificant. This question can be answered by seeing if there are more pulses occurring at six microseconds with the light source than without the source, and this requires counting many such pulses, which would have taken too much film time to do.

(c) A schematic diagram of the photomultiplier is shown.

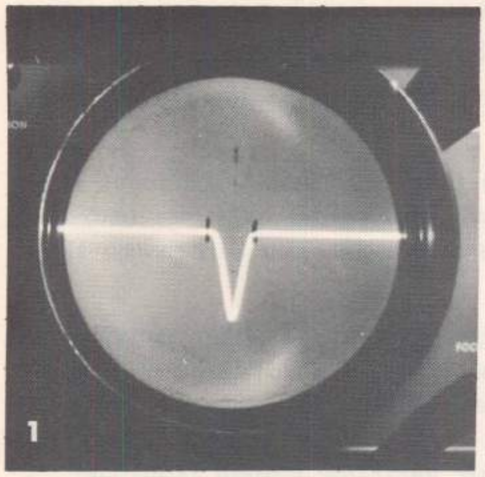


For each electron ejected from the cathode there is a burst of about 10^6 electrons collected at the anode. When the scope is connected to the anode this burst of electrons appears as a single blip (as in Figure 4c).

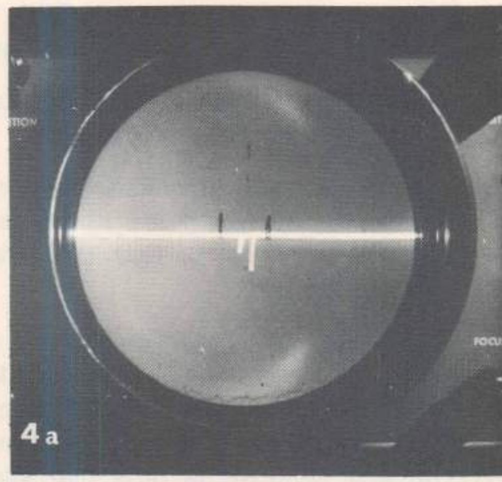
(d) Because of the statistical concepts involved in this film, it might be advantageous to remind the students of the ideas in the film Random Events. For instance, in the photographs (reproduced from Photons), as the light intensity is decreased the number of photoelectrons emitted is decreased and the pulse shape becomes less reproducible. The light beam was turned on at the first mark and turned off at the second.

With no filters (Fig. 1) the effect of the many electrons forming the pulse cannot be noticed, i.e., the shape of the pulse is smooth.

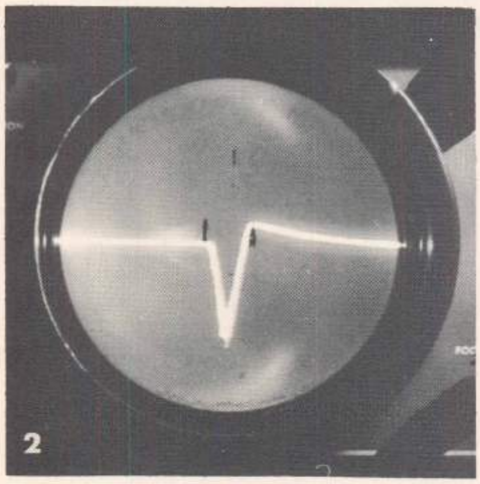
Photons - (3)



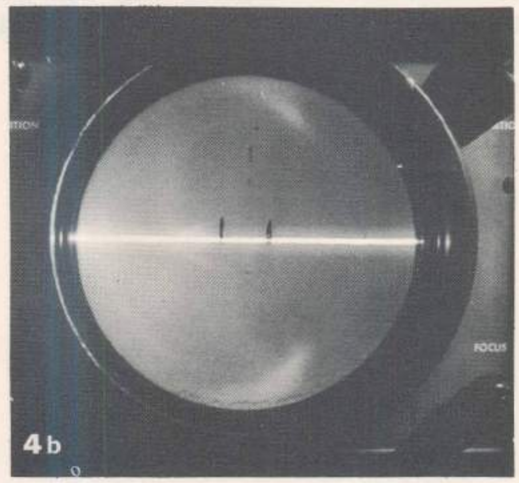
1



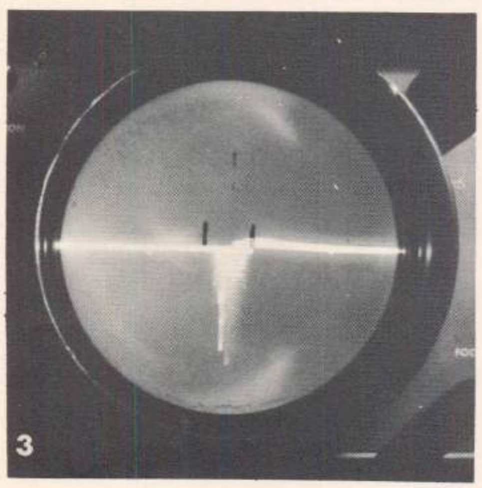
4a



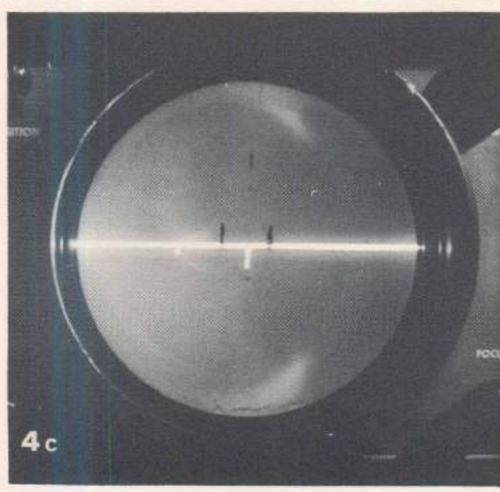
2



4b



3



4c

As seen in Figures 2 and 3, (when 1 and 2 filters are used respectively) the effect of the individual electrons becomes successively more noticeable.

With three filters (Figures 4a, 4b, and 4c) the intensity is so low that we can easily distinguish the effect of each electron.

In 4a we see the effect of two electrons, in 4b there are none, and in 4c there is one. Obviously the pulse shape is completely unpredictable from only one oscilloscope trace. Note in 4c that the effect of a thermal electron is seen before the light beam is turned on.

(e) Students may be puzzled by the lack of uniformity of the pulse amplitudes. If each pulse originated from one electron why are the pulses not all the same size? The reason for the variation in amplitude is the statistical nature of the multiplication process. Sometimes the multiplication at each dynode gives four electrons per incident electron and sometimes only one and so on. The major variation comes from the first dynode where the number of electrons involved is smallest.

TEACHER'S GUIDE TO THE PSSC FILM

PHOTOELECTRIC EFFECT (28 min.)

John Strong, The Johns Hopkins University

A quantitative experiment establishes the relation between the maximum kinetic energy of photoelectrons and the frequency of the incident light. From the observed proportionality, it is concluded that the light energy comes in packets (photons) $h\nu$ in size.

This film relates to Sections and of the PSSC text.

Summary:

Some qualitative experiments demonstrate that sunlight or light from a carbon arc falling on a metallic surface may eject electrons. It is determined that both the color of the light and the type of metal on which the light is incident play a role in this photoelectric effect.

In the main experiment, Professor Strong proceeds to determine quantitatively the relation between the maximum energy of the emitted photoelectrons and the frequency of the incident light. His apparatus consists of a phototube with a potassium photocathode, and a mercury lamp with filters to select monochromatic light. The retarding potential necessary to just stop the photoelectrons from reaching the anode is measured for yellow, green, blue, violet, and ultraviolet light. A plot of the retarding potential versus the frequency of the light is a straight line. Graphs are also exhibited showing the results of similar experiments with sodium and lithium by Millikan in 1916. All the graphs are straight lines with the same slope and are described by the relation $E = h\nu - h\nu_0$. It is shown that the term $h\nu_0$ is a property of the metal photosurface, whereas the term $h\nu$ is characteristic of the incident light. The conclusion is that light energy is absorbed in packets of $h\nu$.

Points for Discussion and Amplification:

(a) The fact that the energy carried by light of frequency ν comes in discrete units, $h\nu$, is just one aspect of the particle-like behavior. In dynamical situations such as the Compton effect it is shown that this amount of light energy also has associated with it a discrete momentum. (See PSSC text, Section 33-6.)

(b) In the experiment, Professor Strong used a front-surface-concave mirror (rather than a glass lens) to focus the light on the potassium. This enabled him to use the ultraviolet part of the mercury spectrum, which is normally absorbed by glass. He could have used a quartz lens, since very little ultraviolet is absorbed by quartz; indeed, the mercury lamp he used was made of quartz.

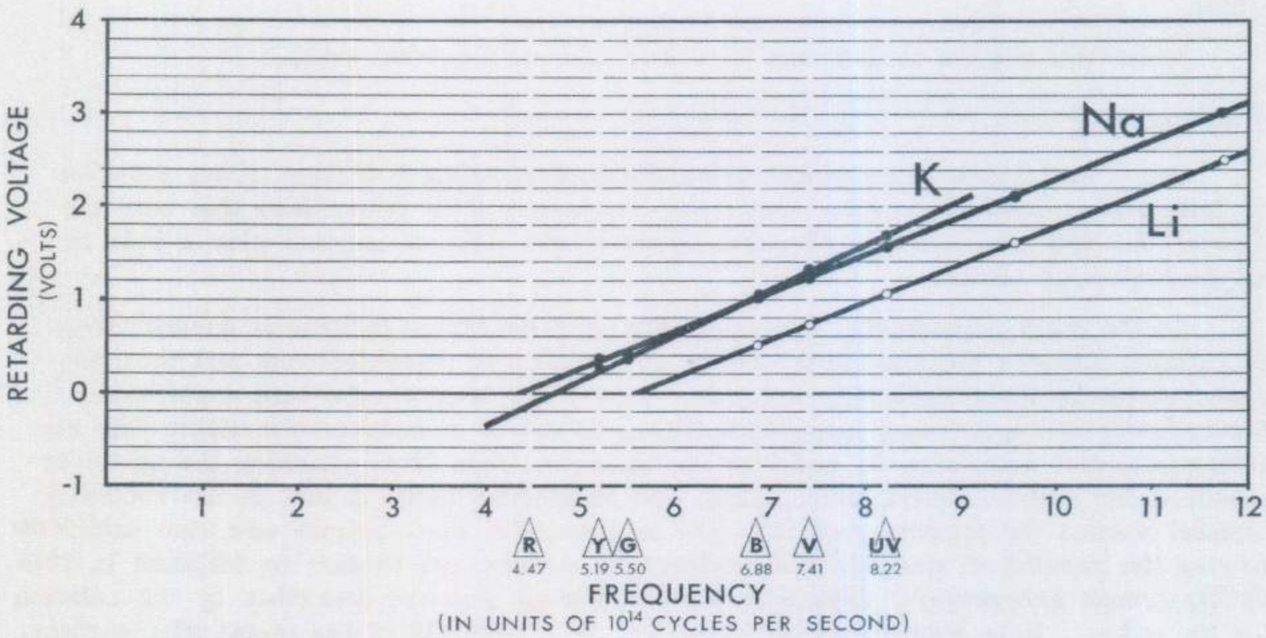
(c) Since filters were employed, students may wonder why a line spectrum source (mercury light) was used instead of a continuous spectrum source (carbon arc). A sharp spectral line of an element, such as mercury, gives more accurate data than the broad spectral band of a filtered continuous spectrum.

Photoelectric Effect - (2)

(d) A detailed presentation of the photoelectric effect is presented in Sections 33-4 and 33-5 of the PSSC text.

(e) Millikan's data (published in The Physical Review, Vol. 7, p. 335, 1916) and the data from the film are reproduced here. The colors of the light used are indicated at the corresponding frequencies.

The value of the slope of the lines (Planck's constant) from Millikan's data is much closer to the accepted value than the slope determined from the data of the filmed experiment.



(f) Potassium was used in this experiment because the photoelectric effect with potassium occurs over a wide range of the visible spectrum. However, the photoelectric effect with potassium does not occur with red light (as can be seen on the graph above).

Wave-Particle

What does a physicist mean when he uses the word "wave"?

(let us try to strip the concept of irrelevant illustrations or metaphors)

In any wave phenomenon --
energy is transfered with a definite, measurable, calculable velocity -- a "disturbance" (a change) is propagated

the change -- vector-fashion -- has magnitude and direction; this is evident in the repeating cycle:

waning, reversing, waxing,
waning, reversing, waxing,
waning, . . .

rhythmic in time, regular in space

The operational criterion is the successful demonstration of an interference pattern (geometrically or temporally) -- cancellations alternating with enhancements:

cancellations and enhancements are produced as in composing vectors -- with magnitudes and directions to be "added" both algebraically and geometrically

What does a physicist mean when he uses the word "particle"?

(the word can be used loosely to refer to micro-meteor, colloidal crumb, molecule, positron...)

There are two aspects to the concept of particle:

(i) "something" is composed of indistinguishably identical, indivisible quantities

the operational criterion is to measure quantities that are either identical, indivisible units or small whole number multiples of such an indivisible unit (so much so, that when small-whole-number relationships show up in data or calculations from data, the inference of "particle" follows today as a matter of convention)

(ii) instantaneous point-location in space and time; a "particle"- "here, now" - has "this velocity" (is on its way "in this direction" at "this speed")

the operational criteria are: observing or recording "tracks", "orbits", "trajectories"; predicting, then verifying ricochets

(the uncertainty principle has amended this second aspect of "particle": both location and velocity for a "particle" cannot be determined with unlimited accuracy - unless some unpredictable "break-through" in scientific inquiry and theory occurs)

The wave-particle delemma describes the astonishment of physicists when they discovered that radiation and the finest sub-divisions of substance have both "wave" and "particle" characteristics. The concepts as developed in classical physics were mutually exclusive. A scientist can choose the experiment that reveals either the "wave" or the "particle" behavior of, say, either electrons or sodium yellow light. The principle of complementarity acknowledges the paradoxical richness of the world we investigate. More important, contemporary physicists have resolved the delemma mathematically to the envigoration of research and the greater precision of their predictions!

"visible light"

"Visible light" -- that illumination which illuminates our world for our sensitive retinas, providing us with the sensations of color and form -- is understood, investigated, and controlled by the scientist as:

--a form of energy (radiation, in transit through free space completely disengaged from "matter"); the form in which energy from our sun so richly floods our terrestrial environment that we receive in one minute as much as the world's economy converts in a year!

--transmissable through free space at a characteristic velocity of 2.997929×10^{10} cm/sec (186,000 mi/sec) which is the maximum, limiting velocity for any material body in our physical universe = c (this is an absolute on which all observers can agree, no matter how they are moving relative to the source); this velocity is mathematically involved in the mass-energy interconversion calculation: $e = mc^2$!

--a wave phenomenon, purely transverse, one of 60 octaves in the vast, continuous spectrum of radiation; as in any wave phenomenon -- $c = \lambda f$!

--an electro-magnetic field phenomenon (the transverseness of the wave the same as that revealed in the Oersted effect: c, H, and E mutually perpendicular); what waxes, wanes, reverses, waxes, wanes, reverses,..rhythmically is the transverse electrical field and the transverse magnetic field associated with it!

--emitted when electrons "fall" from one orbit to another among the particular orbits possible for each kind of atom -- toward the nucleus;

--emitted and received as quanta (particles, photons, corpuscles); all the quanta of a particular frequency are identical, indivisable quantities of energy ($e = hf$) where "h" is Planck's constant, another fundamental proportionality constant describing our particular physical universe ($h = 6.6252 \times 10^{-27}$ erg·second); this constant is involved in the degree of subdivisibility of radiant energy, as in what might be a limit to the precision of man's knowledge of his world! yet the spectrum is continuous, the array of possible frequencies infinitely subdivisible!

CASE WESTERN RESERVE UNIVERSITY · CLEVELAND, OHIO 44106

March 19, 1982

Mr Richard Heckathorn
Midpark High School
7000 Paula Drive
Berea, OH, 44130

Dear Dick,

Thanks for the "resolution". I like to do a quickie: I put up a book with a Roman numeral II in it, as well as some Roman numeral I 's. How far from the book do the I's and II's look the same? That gives the resolution.

I have not tried to do it with filters, but I point out that filters do cut down light intensity, with some loss of acuity. I suppose you could try red and blue cellophane. Light intensity will probably talk harder than wavelength; that's a trouble. Do wear your distance glasses for the experiment, since you are not trying to test how well you focus, but how well you resolve.

It was fun to see you last Saturday!

Sincerely,

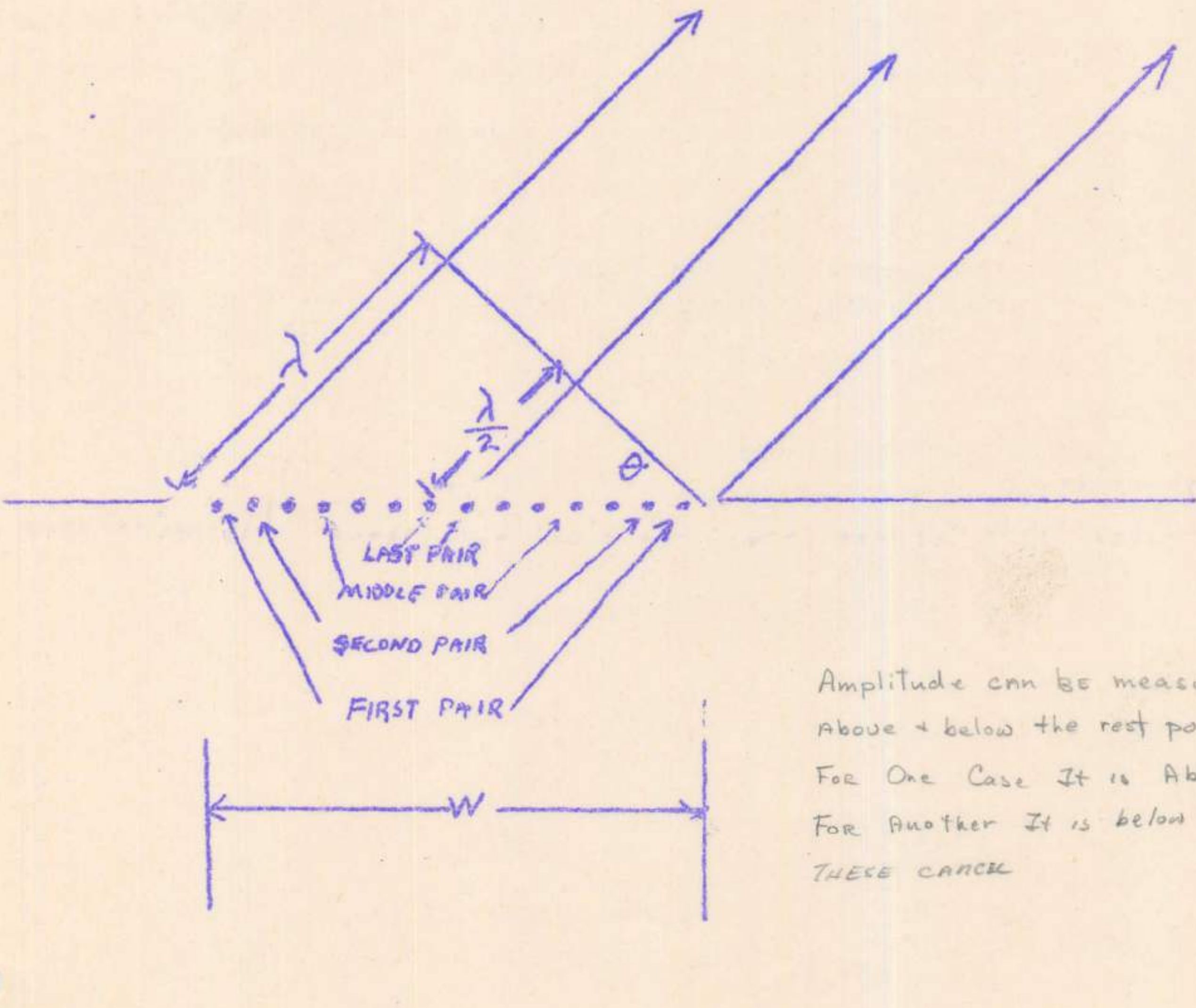
Stefan

Stefan Machlup

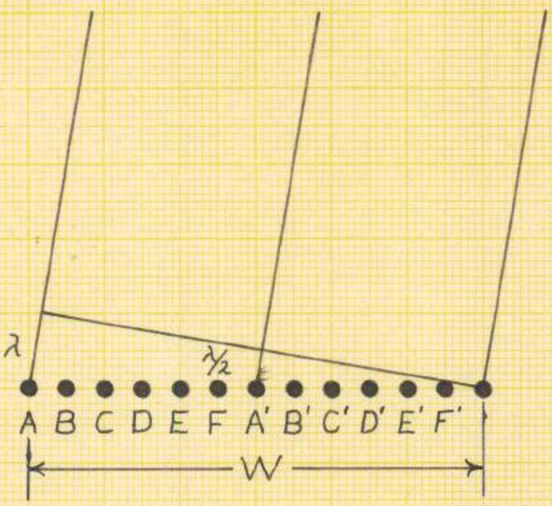
Department of Physics

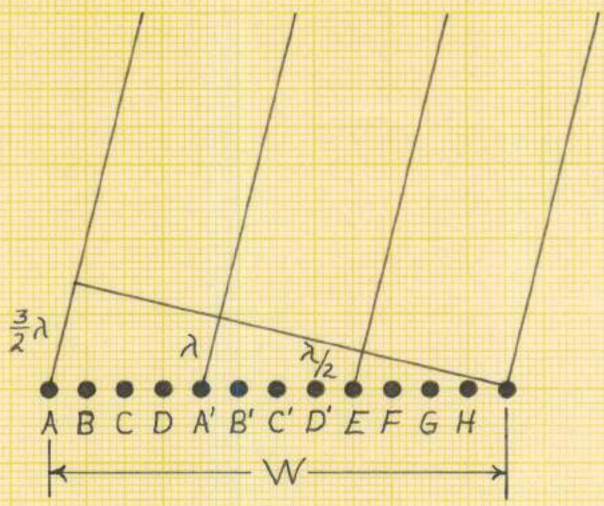
AN EXTRA CREDIT THOUGHT PROBLEM

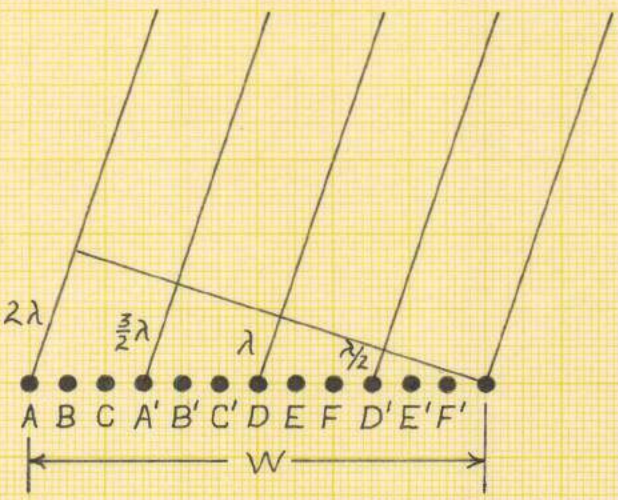
Referring to Figure 19-13 page 293 PSSC physics text:
A student suggests that if you take the point "sources" in the order shown below, the waves from the first pair will add, the second pair will also add but will give an amplitude a little less than the sum of the separate amplitudes. Succeeding pairs will also add, each successive pair giving less until the middle pair cancel. Following pairs then begin to add until the last pair gives an amplitude equal in intensity to the first pair. The result of pairing off sources in this way does therefore, not give a node for $\sin\theta = \lambda/W$. This is in direct contradiction to the result obtained in the text. Where it the fallacy in the argument?

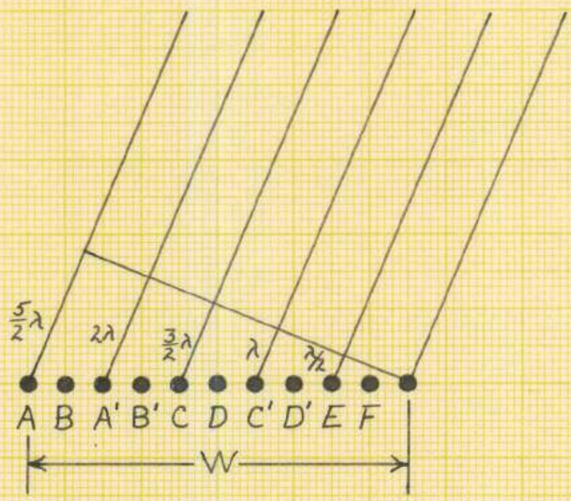


Amplitude can be measured Above + below the rest position. For One Case It is Above, For Another It is below : Thus THESE CANCEL


λ
λ/2
A B C D E F A' B' C' D' E' F'
W


3/2 λ
λ
λ/2
A B C D A' B' C' D' E F G H
W


2λ
3/2 λ
λ
λ/2
A B C A' B' C' D E F D' E' F'
W

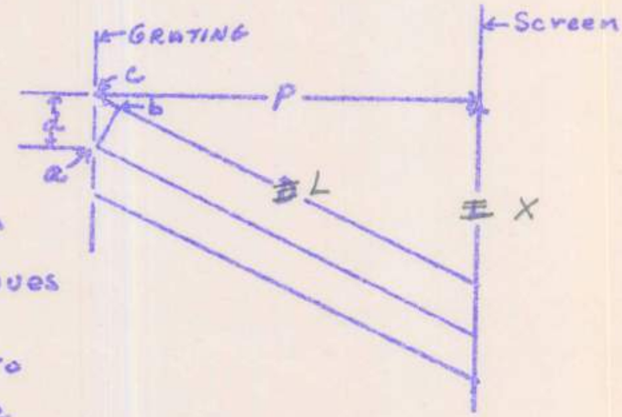

5/2 λ
2λ
3/2 λ
λ
λ/2
A B A' B' C D C' D' E F
W

THE DIFFRACTION GRATING

(A SERIES OF OPAQUE + TRANSPARENT REGIONS)

A. ELEMENTARY THEORY OF THE GRATING

1. A SOURCE BEHIND LONG NARROW SLIT ($\perp$ TO PAPER)
2. THE DISTANCE FROM SLIT TO GRATING LARGE
   ∴ WAVES CONSIDERED TO HAVE PARALLEL WAVE FRONTS AT THE GRATING
3. AT GRATING, WAVELETS AGAIN SPREAD OUT IN EXPANDING CIRCLES (EACH SLIT IN GRATING A CENTER)
4. RAYS OF WAVEFRONTS MAKE AN ANGLE θ WITH DIRECTION OF RAYS ARRIVING AT GRATING.

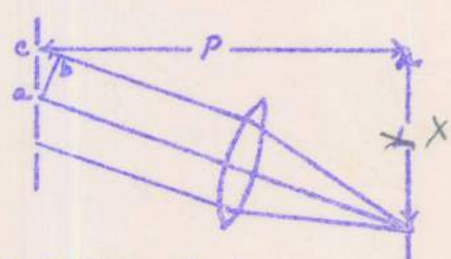


   P = distance FROM GRATING TO SCREEN

   d = distance BETWEEN SLITS or GROOVES

   RIGHT TRIANGLE P-D-L SIMILAR TO RIGHT TRIANGLE d(ac) - ab - bc

5. NOW WAVEFRONT PASSING THROUGH (c) will travel DISTANCE (bc) GREATER THAN WAVEFRONT THROUGH (a).



6. IF (bc) = 1λ, then WAVE FROM (a) AND (c) ARRIVE IN PHASE IN the LENS. THUS THERE IS REINFORCEMENT IN THE IMAGE PRODUCED BY THE LENS
7. THIS IS ALSO TRUE IF (bc) = $n\lambda$ where $n = 1, 2, 3, \ldots$ THEN A BRIGHT IMAGE OF THE SOURCE PRODUCING THE LIGHT INCIDENT ON THE GRATING WILL BE FORMED AT DISTANCE X ~~(E)~~ FROM THE CENTRAL AXIS.

   (NOTE THAT (d) VERY SMALL COMPARED TO P, L, and X)

8. $\frac{cb}{ca} = \frac{X}{L}$; NOW $cb = n\lambda$ $\therefore \frac{n\lambda}{ca} = \frac{X}{L} \Rightarrow \lambda = \frac{dX}{L}$ when $n = 1$

   $\therefore \lambda = \frac{n\,d\,X}{D}$ $n = 1$; 1st ORDER SPECTRUM
   $n = 2$; 2nd ORDER SPECTRUM

$\Delta X = \frac{L}{d}\lambda$

INTRODUCTION

The basic principles of laser operation were predicted by Schawlow and Townes in 1958, and in 1960 the first operating laser was developed. Shortly after that, Spectra-Physics was organized to produce lasers for commercial use. In 1962, our first laser was offered to the public.

Since that time, thousands of Spectra-Physics lasers have been sold for applications ranging from aligning storm and sanitary drain pipes to teaching optics in science classes. Light from our lasers has been bounced off the moon, used for eye surgery, and used to measure the height of ocean waves. Your laser, although of low power, exhibits the same properties that made these applications possible.

There have been many stories in the popular press regarding spectacular applications of laser light—about how it can drill holes in diamonds and vaporize metals. Although very powerful ruby and carbon dioxide lasers can be used for these purposes, this helium-neon laser is quite different. It produces one half of one-thousandth of one watt (0.0005 watt). You can work with it with absolute safety to your skin and clothes.

Nevertheless, the laser, like the sun, is an intense light source; common sense dictates that you never stare directly into the laser beam or position it such that others may look directly into it.

However, you can view the laser beam striking an object such as a wall or screen with complete safety. You need only avoid the direct beam and its reflection in a mirror or other highly polished surface.

Laser light differs from ordinary light in several important and useful respects.

The laser beam is highly *collimated*. That is, the beam spreads very little after being emitted from the laser tube; its *divergence* is low. A conventional light bulb emits light in all directions, and its energy is quickly dissipated. However, laser light can be directed in a narrow beam for great distances. As the beam leaves the laser it is about 1/16 inch in diameter; 20 feet away, it will have spread to only about 1/4 inch.

Laser light is also very *intense*. Because of the low divergence and small spot size, the direct beam from your 0.5 milliwatt (0.0005 watt) laser is more intense than the light from a 100 watt light bulb; you can see the spot from the laser beam even with the lights on. Light intensity is measured in terms of power per unit area. Your laser produces 0.5 mW of radiant power over an area of about 2 square millimeters; this is an intensity of 0.025 watts/cm^2. For comparison, the intensity of the sun is about 0.135 watts/cm^2.

While the light from the sun is more intense, it is made up of many different colors. The primary light from your laser, however, is *monochromatic*, or made up of one single color—bright red. Its wavelength is 632.8 nanometers (0.0000006328 meters). Because of this, you will still see the red spot produced by the laser beam even in bright sunlight. The monochromatic nature of laser light can be likened to the single frequency of a tuning fork or an electronic sine-wave generator. Although the primary light output of your laser is at 632.8 nm, there is also noticeable discharge light in the blue and green wavelengths, a characteristic of He-Ne lasers.

Besides being monochromatic, laser light is *coherent*. This means that, in addition to having only a single wavelength, all the light at a particular point in the beam at a particular instant in time also has the same phase, amplitude, and direction. The low divergence of the laser beam is largely a result of its coherence and the construction of the laser tube itself.

MODEL 155 COMPONENTS

The Model 155 laser consists of the following major components:

1. Plasma tube (see Figure 1)
2. Power supply printed circuit board
3. Power supply transformer
4. Protective housing
5. On/Off Switch
6. Beam attenuator
7. Laser radiation emission indicator
8. Power cord

THEORY OF OPERATION

The name **LASER** is actually an acronym which stands for Light Amplification by Stimulated Emission of Radiation. Although this describes the production of laser light to the scientist, most people desire a more thorough explanation. In order to understand the operation of the laser, it is first necessary to understand how light is produced from electrons.

In all atoms, electrons usually occupy well-defined orbits around the nucleus. Although these electrons can be excited to higher energy states, they will eventually fall back into their normal or ground state; when they do, they emit radiation. If the difference between the excited state and the ground state is within certain limits, the radiation is visible as light. This change in state is called an energy transition, and the radiation from a single transition is called a photon.

In a conventional light bulb, tungsten atoms are excited by an electric current. The transition back to the ground state is random, and photons are emitted in all directions, each with a different frequency, phase, and energy.

We get laser action when many electrons make the same energy transition at the same time. This can occur when many of the same kind of atoms are excited in a small area. Then when one transition occurs, and a photon is emitted, the photon is likely to collide with another excited atom. This collision produces two photons which are like twins;

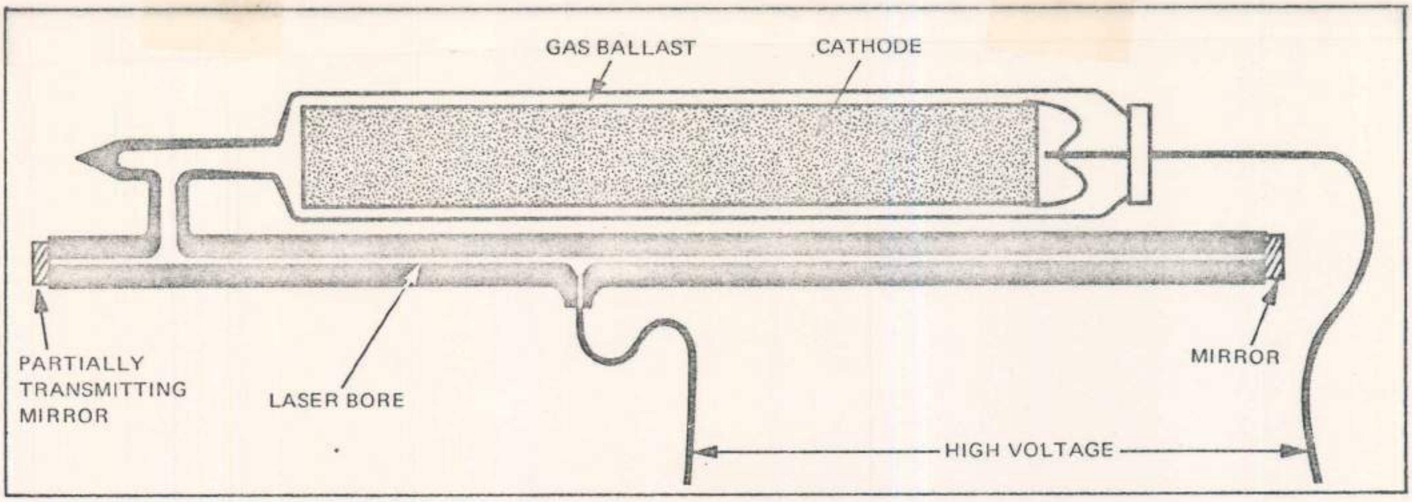


Figure 1. The 155 laser tube.

they are identical in frequency, phase, energy, and direction. When this happens on a large scale, laser light is produced.

In a helium-neon (He-Ne) laser, the desired transition occurs in the neon atoms. The helium helps to excite the neon. An electric current passed through the laser tube easily excites the helium atoms; when these collide with the neon atoms, energy is transferred, and the neon atoms are left excited.

By enclosing the gas in a sealed tube with mirrors on both ends, the photons released in neon energy transitions are reflected back and forth. These photons collide with other excited neon atoms and more photons are released. These collisions build up until there is a continuous flow of photons producing a very intense beam of coherent light along the axis of the tube.

To get the beam out of the laser tube, one of the mirrors is partially transmitting; while it reflects most of the light back, it lets a small portion through. This is the beam you see (Figure 1).

CIRCUIT DESCRIPTION

> WARNING—HIGH VOLTAGES: This laser product contains electrical circuits operating at HIGH VOLTAGES. THESE HIGH VOLTAGES ARE LETHAL.

The protective housing of this laser product is not intended to be removed by the user. It is recommended that any maintenance or service requiring access to the interior of the laser be performed by a Spectra-Physics representative.

Input power is transmitted through the line cord, fuse F100, and On/Off switch S100 to high voltage transformer T100, also lighting the incandescent emission indicator. High voltage transformer T100 primaries are connected in series for 220 V operation or in parallel as shown for 115 V operation. Taps 2 and 2, rather than 3 and 6, are used for 100 V operation.

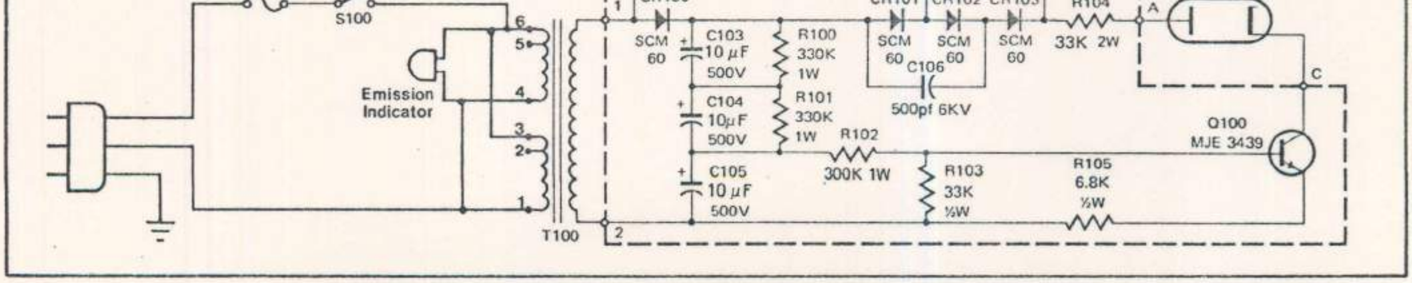


Figure 2. Model 155 Schematic

The secondary of T100 provides 1245 V AC across terminals 1 and 2. This is rectified by half-wave diode rectifier CR100 producing a peak (no load) voltage of 1700 V DC, filtered by R-C filter network capacitors C103, C104, C105, and resistors R100, R101, R102, and R103.

When the Model 155 is initially turned on, the plasma tube, whose anode is connected to point A and cathode to point C, is not ionized and therefore not conducting. An initial high voltage is required to ionize the gas in the plasma tube. This high voltage is provided by the start boost circuit consisting of capacitors C100, C101, C106 and diodes CR101, CR102, and CR103. The start boost circuit provides a voltage at its output about 1000 volts higher per stage than the input voltage. Since there are three stages, the output of this circuit at point A (the anode of the plasma tube) is about 3000 + 1700 volts = 4700 volts. This voltage appears as a short pulse and voltage decreases as the tube conducts. Voltage across the plasma tube under normal operating conditions is about 1000 V DC. Additional components of the circuit are ballast resistor R104, current-regulating transistor Q100, and current-sampling resistor R105.

OPERATION

Operation of the Model 155 laser is simple and straightforward.

1. Point the laser toward a dull surface in a direction that will not intercept anyone's line of vision.
2. Remove the tape covering the output aperture. When the laser is not in use, it is advisable to replace the tape to avoid contamination of the outside surface of the neutral density filter by dust.
3. Leave the beam attenuator in the Off position.
4. Connect the power cord to a 115 V 50/60 Hz receptacle (220 V for European models; 100 V for Japanese models).
5. Turn On/Off switch to On.
6. The emission indicator should light, indicating that power has been applied to the laser.
7. Move the beam attenuator to the On position.
8. A thin red beam of light should be coming from the output aperture of the laser. If the red output beam does not appear within a few seconds, see the section on troubleshooting.

SARGENT-WELCH REPLICA GRATINGS

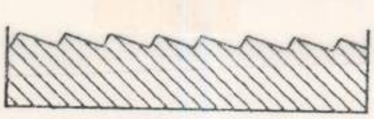
Replica gratings are made by transferring a very thin, hard film from a master grating to a plate of best quality glass. Each replica grating is tested on a precision spectrometer for sharpness and resolution of the diffracted spectral lines (images of the slit) in the first order. Grade A gratings are selected for better definition and resolution than Grade B. Small imperfections and blemishes occasionally occur in the grating film in spite of careful and meticulous procedures. These in no way impair the usefulness or quality of the grating.

The master gratings used have their grooves ruled with the proper shape so that the light diffracted on one side of the central beam will be principally concentrated in the first order spectrum. The several orders on the other side of the central beam will diminish in intensity normally. Since most measurements are made in the first order, this concentration of light in the first order is often very useful. For measurements in the second order, use the diffracted lines on the other side of the central image.

Replica gratings are made from master gratings having 600 grooves per mm (15240 grooves per inch) and 300 grooves per mm (7620 grooves per inch). These values are used for the replicas even though, due to contraction or sometimes expansion in the transfer process, the actual number of grooves per mm or inch for a given grating may be slightly different from these nominal values.

These values are satisfactory for most work but, when the grating is to be used for very precise determinations, it is suggested that the actual number of grooves per inch be accurately determined by means of a spectrometer and a light source with emission lines of known wavelengths.

Groove form of the usual grating.



Groove form of the master grating from which "Brightline" replicas are made.

APPENDIX 2

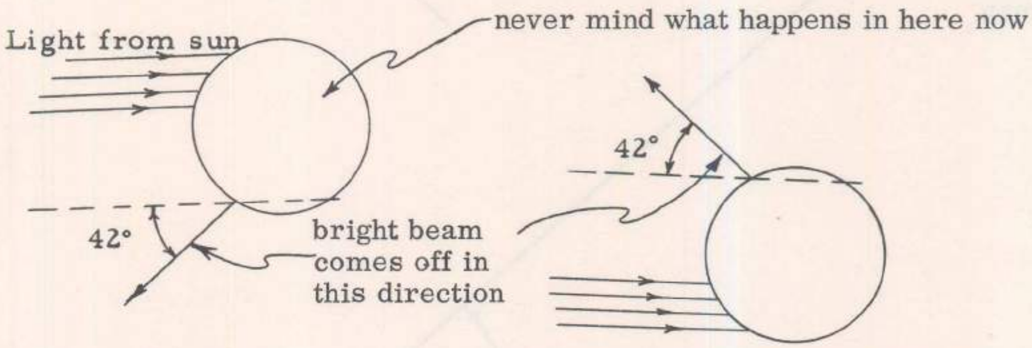
Supplement to Chapter 13: The Rainbow

<u>Why is the rainbow shaped like a bow</u>?

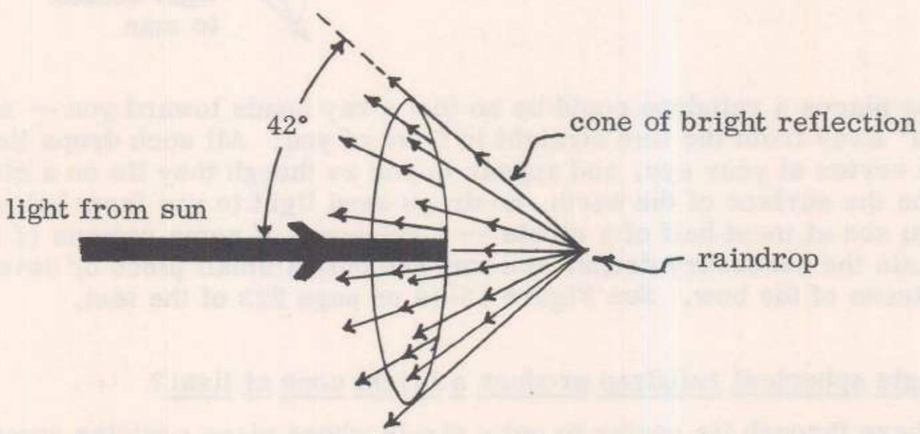
Never mind color now. Think about pure yellow light to see how the bow shape arises.

When a beam of (yellow) light hits a raindrop, some of the light enters the drop, refracts, and reflects. It bounces (never mind which way now) and finally leaves the drop in many directions. For now, all that is important is that in directions which are 42° away from the incoming beam, the light coming back is particularly bright. It is brighter than 41° or 43° or any other nearby direction.

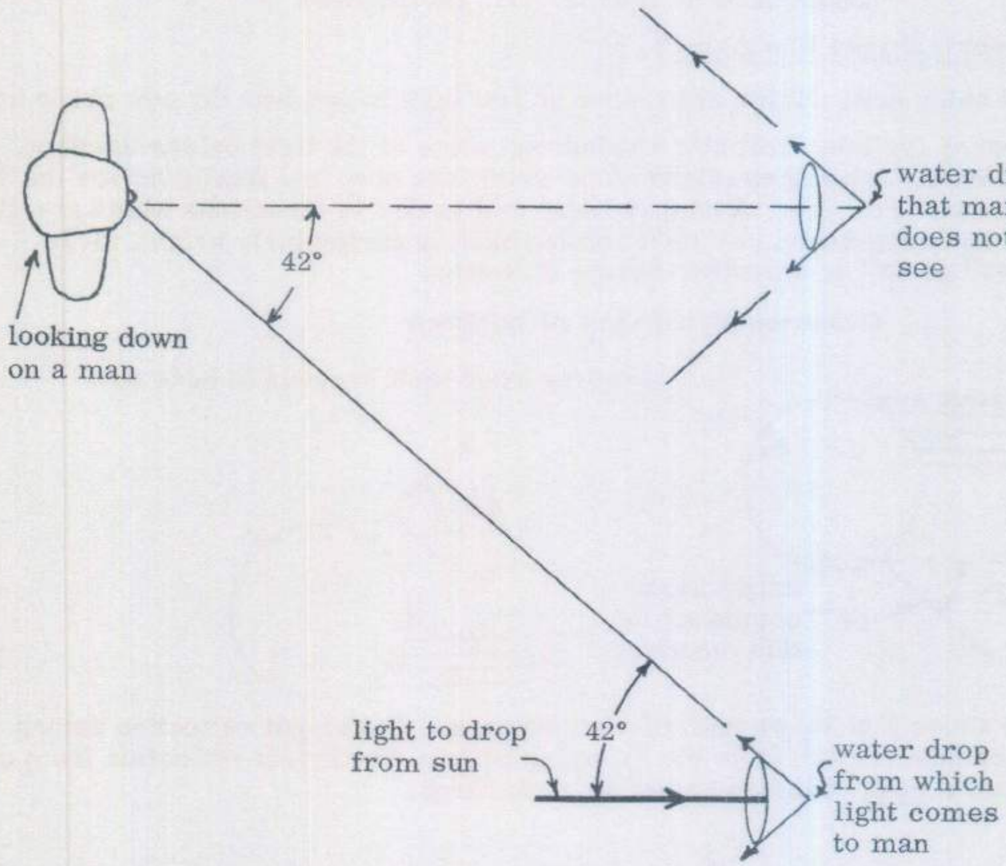
Cross-sectional view of raindrop



The picture above just shows part of what happens. The bright reflection comes back on all lines that are 42° from the incoming beam. The bright reflection from one drop is therefore a <u>cone</u> of light with vertex at the drop.



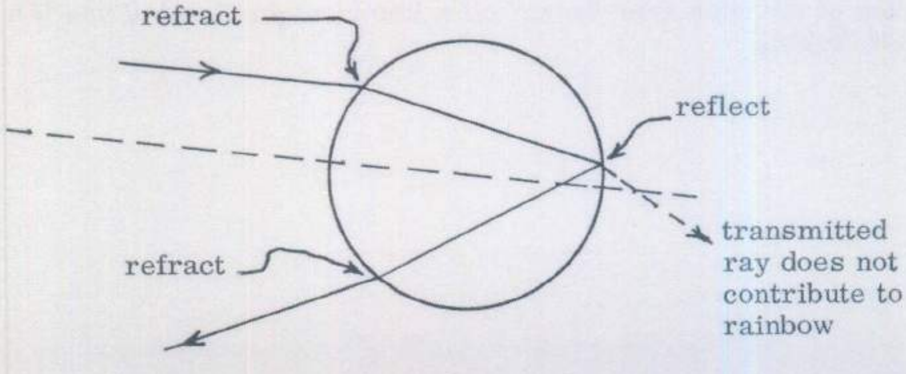
Where must such a cone of light be located in order for a ray moving along the cone surface to head directly toward you, that is, in order for you to see it? A cone whose vertex is directly in front of you would shoot around you on all sides and miss you completely. The vertex of the cone must be 42° off a line straight ahead of you if a ray of the cone is to come to you.



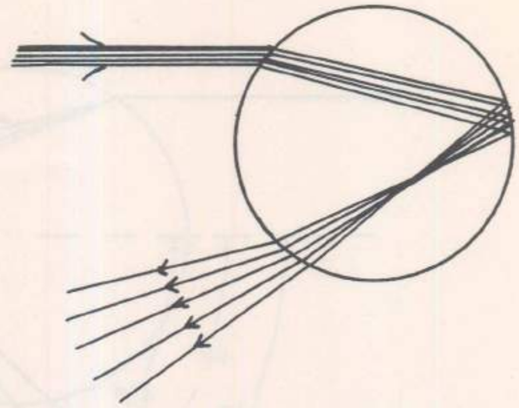
There are many places a raindrop could be so that a ray heads toward you -- any place that is 42° away from the line straight in front of you. All such drops lie on a cone with the vertex at your eye, and appear to you as though they lie on a circle. Since you are on the surface of the earth, no drops send light to you from below ground, and you see at most half of a circle -- a rainbow! If some regions of the sky do not contain the necessary drops, you may see only a small piece or several disconnected pieces of the bow. See Figure 13-19 on page 223 of the text.

<u>Why does a single spherical raindrop produce a bright cone of light</u>?

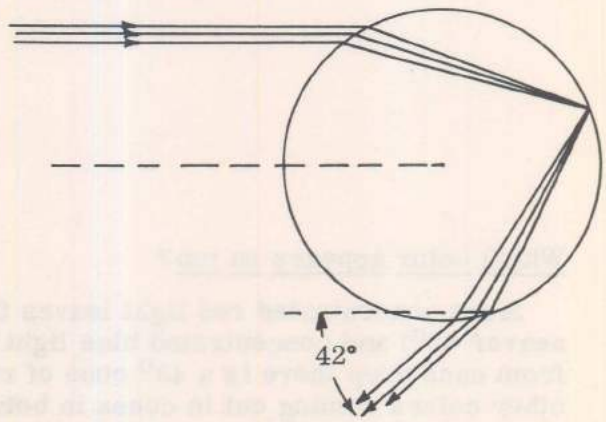
Slice the sphere through its center to get a circle whose plane contains some of the light rays from the sun. One path that a light ray can take is to enter the circle, refracting as it goes from air to water, bounce once at the rear of the circle and refract out when it next hits the surface.



If a narrow parallel beam (much narrower than the width of the drop) of light enters the drop, for most points of entry, it is converted into a diverging beam of light by the time it leaves the drop.



Since the light from such beams spreads out upon leaving the drop, it does not appear much brighter than the rest of the sky to someone looking at the drop. <u>However</u>, there is one <u>ring</u> on the drop (or two points on the drop cross section) where an incoming beam goes out also as a narrow beam.

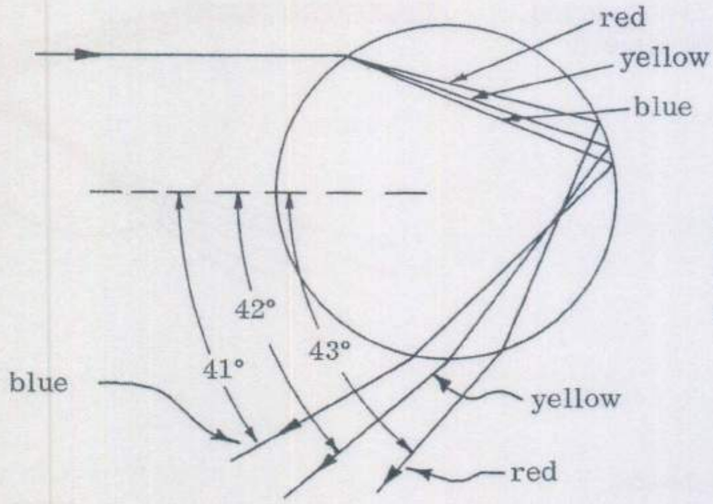


Only a small beam of light into and out of the raindrop accounts for bright 42° cone.

One can check that this is the case by making a sufficient number of accurate scale drawings--all that is involved is refraction and reflection, and you can handle both in a drawing if you work with sufficient care. Since the water drop is a sphere and not a circle, the bright emerging beams leave the drop in a 42° cone as previously mentioned.

<u>Why is the rainbow colored</u>?

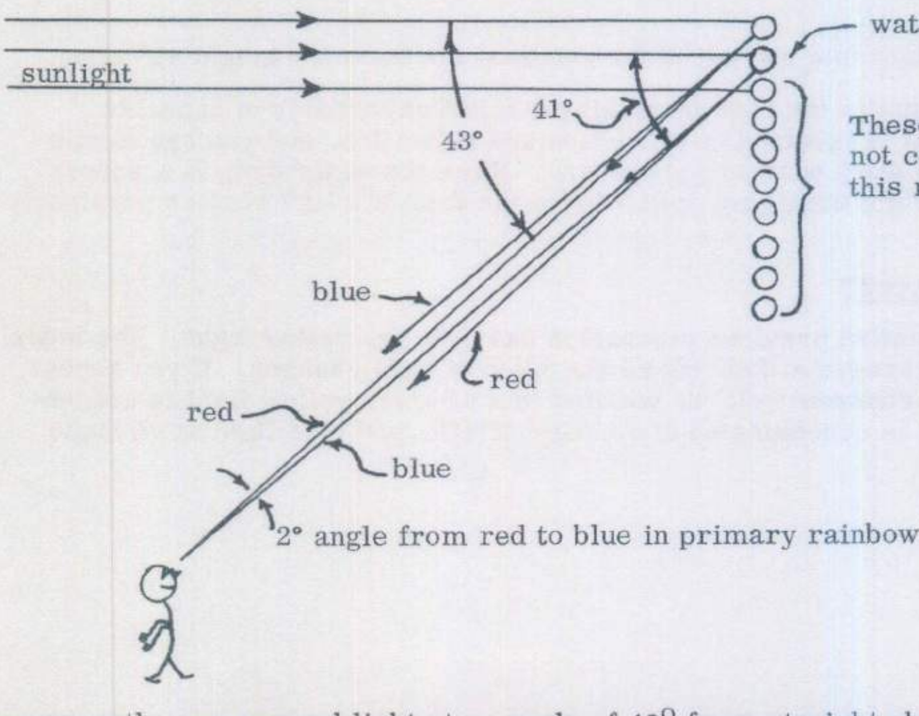
Remember that the entire previous discussion has been for yellow light. The index of refraction of water changes a little bit as the color of light changes. If you repeat the drawings above for different colors, you find that whereas yellow light is concentrated at 42°, red light is concentrated at an angle of 43°, and blue light at an angle of 41° (approximate).



NOTE: Not to scale. The angles between the colors are exaggerated.

Which color appears on top?

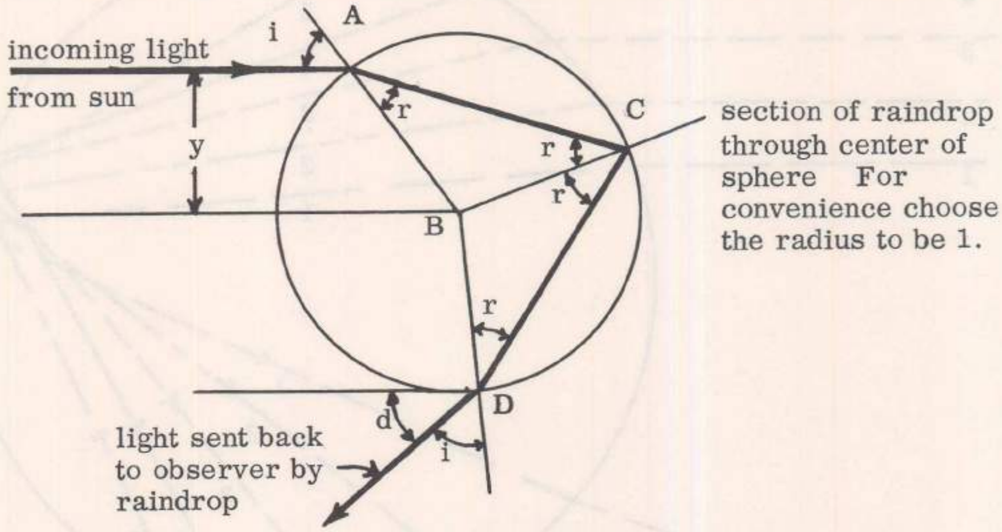
Since concentrated red light leaves the drop at an angle of 43^{O} (42.37^{O}, really nearer 42^{O}) and concentrated blue light leaves the drop at an angle of 41^{O} (40.6^{O}), from each drop there is a 43^{O} cone of red light and a 41^{O} cone of blue light with the other colors coming out in cones in between.



Consequently, we see red light at an angle of 43^{O} from straight ahead (at the outside of the bow) and blue light at an angle of 41^{O} (on the inside). The drops sending any one of the colors to us lie on part of a cone with vertex at our eye, and so appear to lie on part of a circle. Thus every primary rainbow is about 2° wide.

What is the geometry of rays going through a spherical drop?

If we add three radii and some auxiliary lines to Figure 13-17 on page 222, we obtain

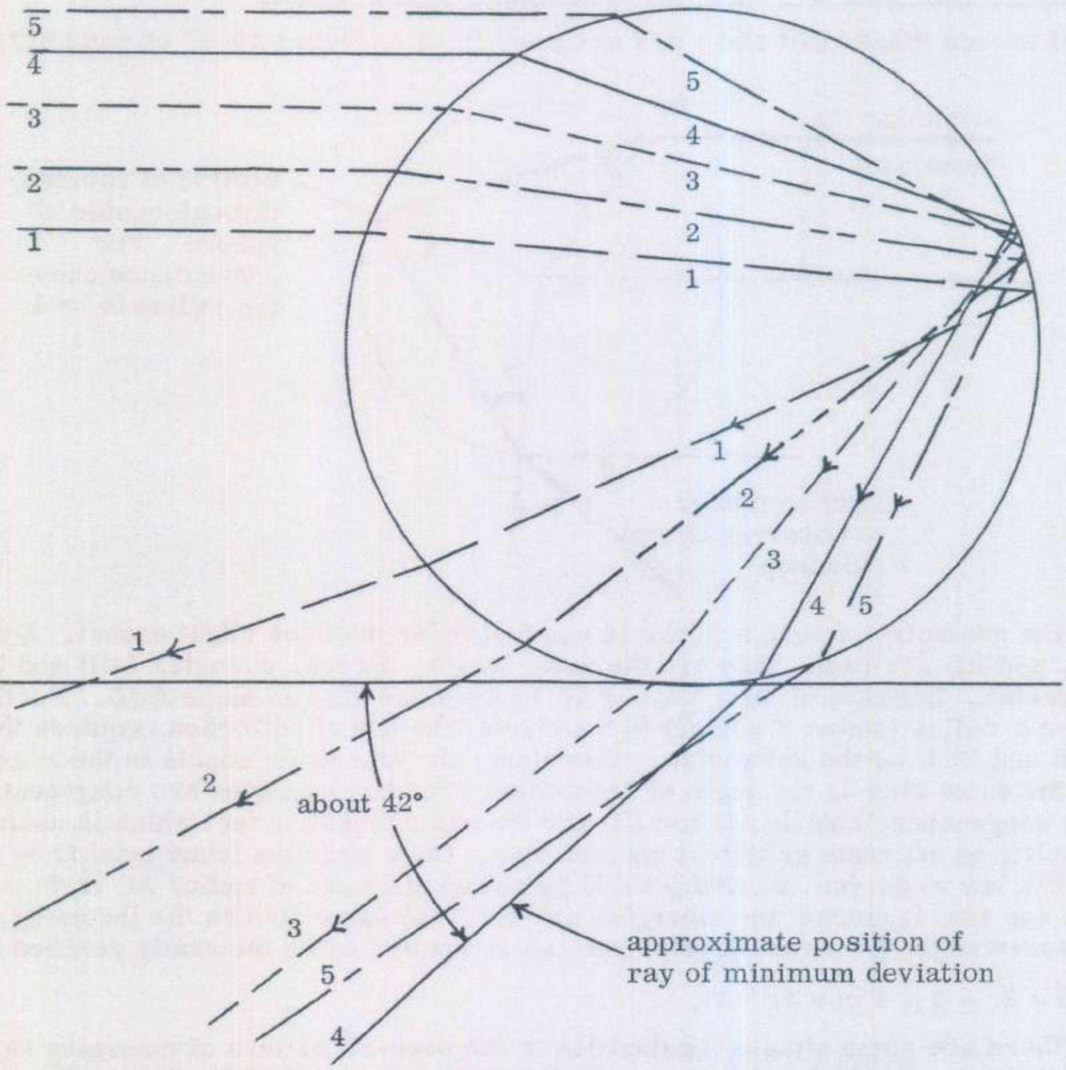


The geometry of such a figure is much simpler than one might expect. Since BA, BC, and BD are radii, they are the same length. Hence, triangles ACB and CDB are isosceles. Because of this, angle BAC is the same size as angle ACB. Furthermore, since a radius is also a normal to the circle, the law of reflection requires that angles ACB and DCB be the same size. Therefore, the four acute angles in the triangles are all the same size as the angle of refraction. The two triangles are congruent. From this congruence, chords AC and CD are the same length, a fact which is useful in simplifying accurate graphical construction. Once you have found point C by using Snell's law at A, you can find point D by swinging an arc of radius AC from point C. You can then construct the emerging angle, i, the same size as the incoming angle and measure angle d. Alternatively, you can compute d using the easily verified equation

$$d = 2r - 2(i - r) = 4r - 2i.$$

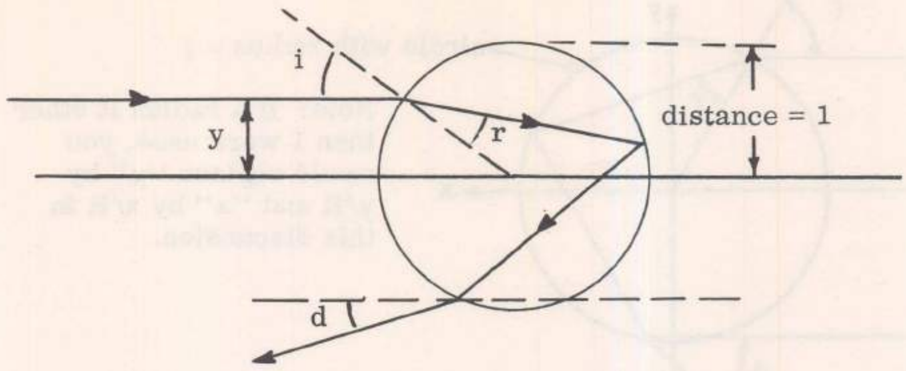
There are some simple regularities in the over-all pattern of emerging rays coming from parallel incident rays striking the upper half of the drop. The ray which approaches along the diameter (i.e., the distance y in the figure above is 0), travels through the center and returns along itself. As the distance y is increased, the point D moves counterclockwise around the circle. At first the angle d increases in size. But at a certain point, as the light enters the circle higher and higher, angle d stops increasing and begins to decrease. The maximum for angle d with yellow light is about 42°. This can be verified by scale drawing or by calculus which shows that d is a maximum when $\cos i = \sqrt{\frac{n^2 - 1}{3}}$.

Here is a diagram of five rays through a drop.



Notice that in this drawing rays 3, 4, and 5 lead to quite different angles, d. These rays do not all contribute to the strong colored light in a rainbow. It is a much narrower band of rays near ray 4 which actually contributes to the rainbow. Remember that the entire rainbow is only about 2^{o} wide so that each color is concentrated in an angular range much smaller than 2^{o}.

(If a student is making a thorough study of rainbows, he should make some scale drawings of the paths of rays in a raindrop.) The ray making the maximum angle with the horizontal is called the ray of minimum deviation. A table of values, more accurate than the drawing above, follows.

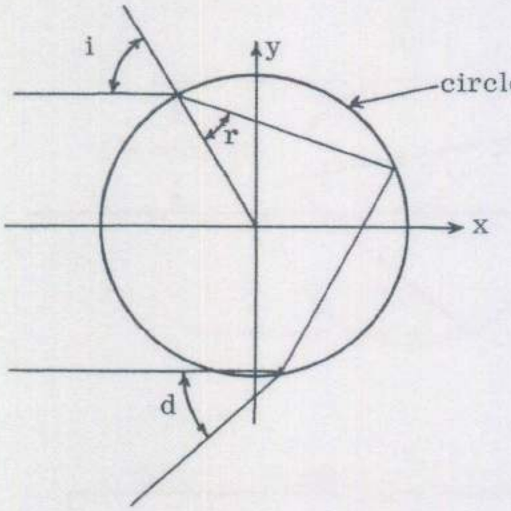


y sin i	i	r	sin r	d
0	0°	0°	0	
0.1	5°44'	4°18'	0.075	5°44'
0.2	11°32'	8°37'	0.15	11°24'
0.3	17°27'	13°00'	0.225	17°06'
0.4	23°35'	17°27'	0.3	22°34'
0.5	30°00'	22°01'	0.375	28°04'
0.6	36°52'	26°45'	0.45	33°16'
0.7	44°26'	31°40'	0.525	37°44'
0.8	53°08'	36°52'	0.60	41°12'
0.8606	59°23'	40°12'	0.6455	42°02'
0.9	64°09'	42°27'	0.675	41°30'
1.0	90°	48°35'	0.75	14°20'

<u>What is the geometry of different colors in a raindrop?</u>

It is along the ray of minimum deviation that the bright returning light is seen. The sketches in the preceding discussion indicate the reason light is concentrated in the region close to the ray of minimum deviation. At angles less than the angle of the ray of minimum deviation, the intensity of the returning light falls rapidly. (We are not treating here the details of how fast the intensity decreases.)

For $n = 4/3$, the minimum deviation occurs at $y = 0.8606$ or $i = 59°23'$. This index applies to yellow light. A ray diagram for violet light or red light would look similar to one for yellow light. Some key numbers that would simplify the drawing of the minimum deviation rays for red and violet are given in the following table.



Note: If a radius R other than 1 were used, you would replace "y" by y/R and "x" by x/R in this discussion.

	Violet Light	Red Light
Wave length	= 3968 A	= 6563 A
Refractive index	n = 1.3435	n = 1.3311
Values on circle representing drop		
Minimum deviation ray	y = 0.855	y = 0.862
enters	x = -0.518	x = -0.507
Ray hits back surface	y = 0.347	y = 0.361
	x = +0.938	x = +0.932
Ray emerges	y = -0.987	y = -0.979
	x = 0.163	x = 0.206
Angle of incidence i	$58^o48'$	$59^o31'$
Angle of refraction r	$39^o33'$	$40^o21'$
i - r	$19^o15'$	$19^o10'$
d	$40^o36'$	$42^o22'$

Because each color comes back in a narrow band of angles, there is some mixing of the colors. This is another topic we are not treating in detail.

All of the geometry of light in a raindrop above has been done in a cross section through the center of the sphere. Any ray of light that hits the sphere will stay in the plane determined by that ray and the normal to the sphere at the point of entry. All such planes intersect the center of the circle and the discussions above apply. Thus you do get a cone of light for each color with its half vertex angle the size of the angle of minimum deviation for each color.

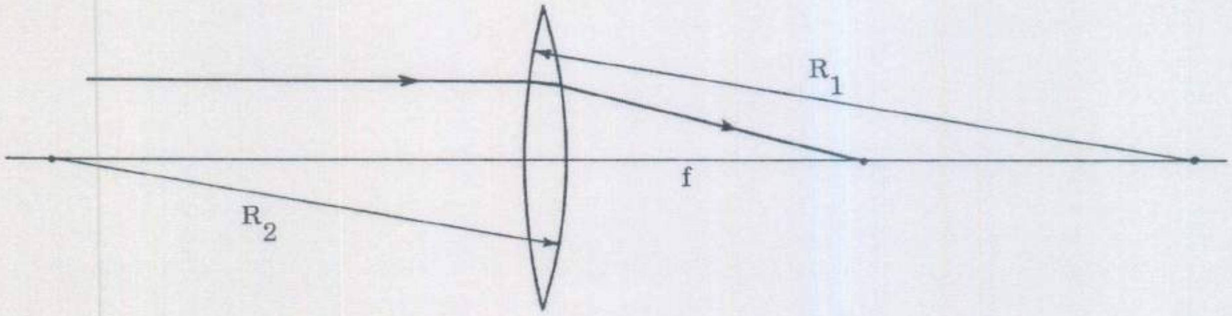
A calculation of the intensity of the rainbow is extremely complicated. (See Physics of the Air, W. J. Humphreys, McGraw-Hill, New York, 1940, page 488ff, edition III.) For drops that are larger than the size of fog particles, the intensity pattern depends not only on the angle, but on the index of refraction, the size of the drop, and the wave length of light. (The intensity is significant only very close to the angle of minimum deviation so that the variation in reflectivity is negligible.) If the drops are the size of fog particles, even more complex calculations are needed which are based on electromagnetic theory.

APPENDIX 3

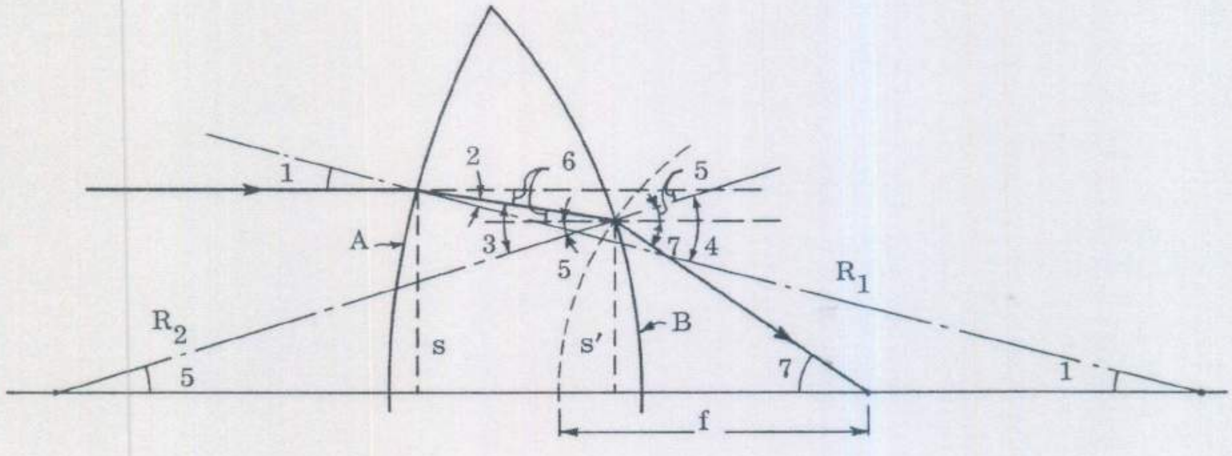
Supplement to Chapter 14, Section 2. Derivation of the Lensmaker's Formula

The following derivation involves no more than Snell's law, geometry, and radian measure.

Since all rays parallel to the principle axis of a lens cross the axis of the lens at a common point (principal focus) it is only necessary to consider one of these rays in deriving this formula.



The above diagram is too small in the lens region through which the ray passes so it is necessary to enlarge and exaggerate the angles in this region.



The refractions of the ray at both surfaces A and B are described respectively by Snell's law as

$$\sin 1 = n \sin 2$$
$$\sin 4 = n \sin 3$$

With a thin lens all of these angles are very small and thus the angles in radians may be substituted for the sines of the angles.

$$\text{(a)} \quad \angle 1 = n \times \angle 2$$
$$\text{(b)} \quad \angle 4 = n \times \angle 3$$

The next step is to reduce these equations to one equation with angles 1, 5, and 7 only. Additional lines have been drawn parallel to the axis of the lens and the equal angles thus formed have been labeled with the same number for simplicity. Adding (a) and (b) gives $\angle 4 + \angle 1 = n(\angle 2 + \angle 3)$, but since $\angle 4 = \angle 5 + \angle 7$ and $\angle 3 = \angle 5 + \angle 6 = \angle 5 + \angle 1 - \angle 2$, this equation (by substitution) is $\angle 5 + \angle 7 + \angle 1 = n(\cancel{\angle 2} + \angle 5 + \angle 1 - \cancel{\angle 2})$.

By rearranging terms and factoring $\angle 7 = (n-1)(\angle 5 + \angle 1)$. From the first drawing we can see that the lines marked s and s′ in the second drawing and the length of the corresponding arcs are all so nearly equal that they can be considered equal. Also since it doesn't really matter to what point in the lens f is measured for a thin lens, a convenient arc was drawn about the focus and f is measured to this arc. Thus, upon substituting the ratios of arcs to radii for the angles in radians the following equation is obtained:

$$\frac{s'}{f} = (n-1)\left(\frac{s'}{R_2} + \frac{s}{R_1}\right)$$

which gives the desired formula upon dividing each term by either of the equalities s or s′.

$$\frac{1}{f} = (n-1)\left(\frac{1}{R_2} + \frac{1}{R_1}\right)$$

It should be noted that the index of refraction, n, used in the above derivation is the relative index of the lens material and the medium in which it is immersed. Thus, if there are two different media on either sides of the lens the first factoring in the derivation could not be done. Diagrams which better portray these ideas are shown below.

($n_{air} = 1.00$, $n_{water} = 1.33$, and $n_{glass} = 1.5$)