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ABSTRACT

This instructional guide, intended for student use, develops the concept of color through a series of sequential activities. A technical development of the subject is pursued with examples stressing practical aspects of the concepts. Included in the minicourse are: (1) the rationale, (2) terminal behavioral objectives, (3) enabling behavioral objectives, (4) activities, (5) resource packages, and (6) evaluation materials. (CP)

CAREER ORIENTED PRE-TECHNICAL PHYSICS

Color

Minicourse

ESEA Title III Project

1974

dallas independent school district

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October 8, 1974

This Minicourse is a result of hard work, dedication, and a comprehensive program of testing and improvement by members of the staff, college professors, teachers, and others.

The Minicourse contains classroom activities designed for use in the regular teaching program in the Dallas Independent School District. Through minicourse activities, students work independently with close teacher supervision and aid. This work is a fine example of the excellent efforts for which the Dallas Independent School District is known. May I commend all of those who had [illegible] part in designing, testing, and improving this Minicourse.

I commend it to your use.

Sincerely yours,

Nolan Estes

General Superintendent

NE:mag

CAREER ORIENTED PRE-TECHNICAL PHYSICS

MINICOURSE ON COLOR

RATIONALE (What this minicourse is about)

Ah! The mystery of color! Color is certainly one of the commonplace things in one's life that adds an aesthetic value (beauty) to objects and materials of all types. A person is always influenced consciously and subconsciously by color. This influence appears when buying clothes, cars, home decorations, furniture, food, and other things.

Besides being an important part of everyday life, color also plays an important role in many careers. Some knowledge of color is mandatory for artists and photographers, as well as craftsmen and technicians in the printing, painting, textile, fashion design, and television industries, to name a few.

As the demand increases for better and more precise color control, more and more people will be employed for the development and production of refined color systems for both industrial and commercial purposes.

In addition to RATIONALE, this minicourse contains the following sections:

1) TERMINAL BEHAVIORAL OBJECTIVES (Specific things that you are expected to learn)
2) ENABLING BEHAVIORAL OBJECTIVES (Learning "steps" which will enable you to eventually reach the terminal behavioral objectives)
3) ACTIVITIES (Specific <u>things</u> <u>to</u> <u>do</u> to help you learn)

4) RESOURCE PACKAGES (Instructions for carrying out the activities, such as procedures, references, laboratory materials, etc.)

5) EVALUATION (Tests to help you learn and to determine whether or not you satisfactorily reach the terminal behavioral objectives):

   a) Self-test(s) with answers, to help you learn more.

   b) Final tests, to help measure your overall achievement.

TERMINAL BEHAVIORAL OBJECTIVES:

When you have completed this minicourse, you will demonstrate a knowledge of color technology by being able to:

1) identify selected basic properties of visible light and work problems using the formula $c=f\lambda$.

2) name the colors in the solar spectrum, give their order or sequence of appearance, give their approximate respective wave lengths, and know that spectra from other sources sometimes differ from the solar spectrum.

3) define color temperature; determine the correct "mixed" value for a particular light source; use a "mixed" nomograph and determine the correct compensating filter for a particular light source.

4) describe selected basic properties of colored materials.

5) name selected basic properties of complementary colors.

6) describe how a rainbow is formed.

7) explain why the sky is blue.

8) explain how colors are produced by thin films.

9) describe selected effects of color on the eye, including such terms as cones, rods,

three-color vision, adaptation, after-image, contrast, aberration and harmony.

10) demonstrate additive color mixing.

11) demonstrate subtractive color mixing.

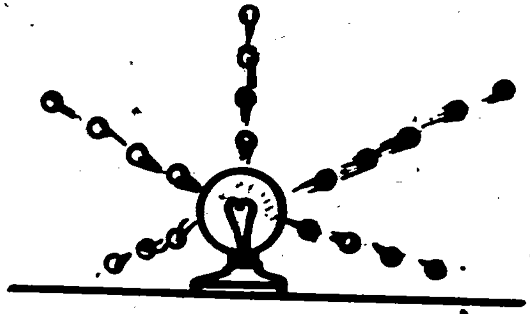
ENABLING BEHAVIORAL OBJECTIVE #1: Identify selected basic properties of visible light and work two (2) problems using the formula, $c = f\lambda$.	ACTIVITY 1-1 Read Resource Package 1-1	RESOURCE PACKAGE 1-1 "Light"
	ACTIVITY 1-2 Complete Resource Package 1-2	RESOURCE PACKAGE 1-2 "Self-Test"
	ACTIVITY 1-3 Check the questions and problems using Resource Package 1-3	RESOURCE PACKAGE 1-3 "Answers to Self-Test"
ENABLING BEHAVIORAL OBJECTIVE #2: Name the colors in the solar spectrum, their wavelengths, and the colors found in some other light source spectra.	ACTIVITY 2-1 Read and complete Resource Package 2-1	RESOURCE PACKAGE 2-1 "Spectrum I"
	ACTIVITY 2-2 Read and complete Resource Package 2-2	RESOURCE PACKAGE 2-2 "Spectrum II"
	ACTIVITY 2-3 Read and complete Resource Package 2-3	RESOURCE PACKAGE 2-3 "Measuring Wavelengths of Colors"
	ACTIVITY 2-4 Answer questions in Resource Package 2-4.1 and check your answers with Resource Package 2-4.2	RESOURCE PACKAGE 2-4.1 "Self-Test"

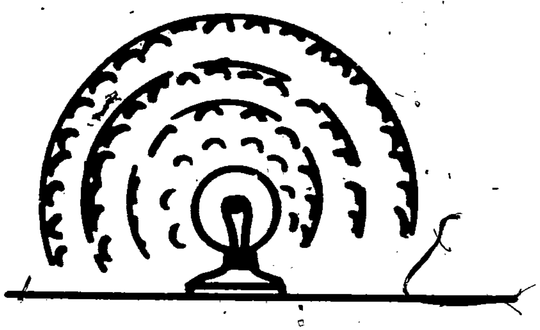
		RESOURCE PACKAGE 2-4.2 "Answers to Self-Test"
ENABLING BEHAVIORAL OBJECTIVE #3: Define color temperature and relate color temperature to color film.	ACTIVITY 3-1 Read and complete Resource Package 3-1	RESOURCE PACKAGE 3-1 "Color Temperature"
ENABLING BEHAVIORAL OBJECTIVE #4: Describe the selected basic properties of colored materials.	ACTIVITY 4-1 Read and complete Resource Package 4-1	RESOURCE PACKAGE 4-1 "Properties of Colored materials"
	ACTIVITY 4-2 Answer questions in Resource Package 4-2.1 and check your answers with Resource Package 4-2.2	RESOURCE PACKAGE 4-2.1 "Self-Test" RESOURCE PACKAGE 4-2.2 "Answers to Self-Test"
ENABLING BEHAVIORAL OBJECTIVE #5: Name some basic properties of complementary colors.	ACTIVITY 5-1 Read and complete Resource Package 5-1	RESOURCE PACKAGE 5-1 "Complementary Colors"
ENABLING BEHAVIORAL OBJECTIVE #6: Describe how a rainbow is produced.	ACTIVITY 6-1 Read and complete Resource Package 6-1	RESOURCE PACKAGE 6-1 "Rainbows"
ENABLING BEHAVIORAL OBJECTIVE #7: Explain why the sky is blue.	ACTIVITY 7-1 Read and complete Resource Package 7-1	RESOURCE PACKAGE 7-1 "Blue Skies"

ENABLING BEHAVIORAL OBJECTIVE #8: Explain how colors are produced by thin film interference.	ACTIVITY 8-1 Read and complete Resource Package 8-1.	RESOURCE PACKAGE 8-1 "Colors in Thin Films"
ENABLING BEHAVIORAL OBJECTIVE #9: Describe the effects of color on the eye; including such terms as cones, rods, three-color vision, adaptation, after-image, contrast, aberration and harmony.	ACTIVITY 9-1 Read and complete Resource Package 9-1.	RESOURCE PACKAGE 9-1 "Color Vision"
ENABLING BEHAVIORAL OBJECTIVE #10: Demonstrate the basic properties of additive color mixing.	ACTIVITY 10-1 Read and complete Resource Package 10-1.	RESOURCE PACKAGE 10-1 "Additive Color Mixing"
ENABLING BEHAVIORAL OBJECTIVE #11: Demonstrate the basic properties of subtractive color mixing.	ACTIVITY 11-1 Read and complete Resource Package 11-1.	RESOURCE PACKAGE 11-1 "Subtractive Color Mixing"

RESOURCE PACKAGE 1-1

LIGHT

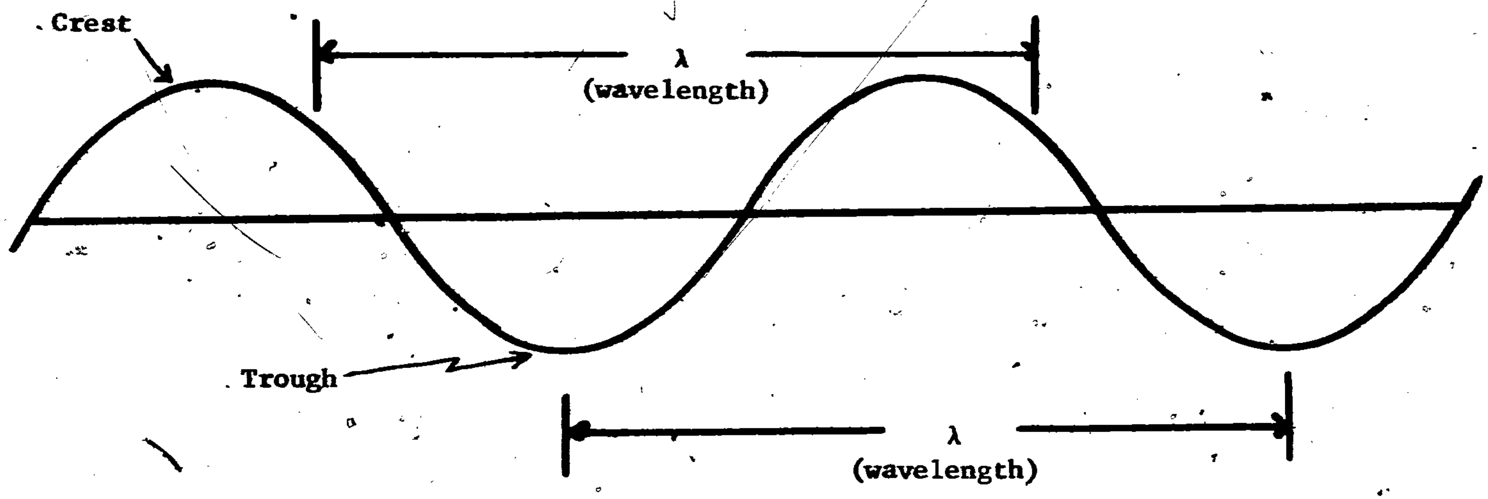

CORPUSCULAR LIGHT


WAVE LIGHT

Before one can talk about color, one should have some understanding about the nature of visible light. To understand the nature of light has been a formidable task for scientists. The nature of light only recently has been reasonably understood. Between the 1600's and the 1900's, scientists disputed over two primary theories about the nature of light. One group said that light consisted of a stream of tiny particles which left from a luminous source, the Newton Corpuscular Theory. At the same time it was argued that light traveled in the form of waves (waves with characteristics similar to waves produced by dropping a stone into a pool of quiet water), the Huygen Wave Theory. Next, James Maxwell showed light to be a form of wave energy that travels through space (or other medium). Moreover, he showed that visible light is part of the <u>electromagnetic spectrum</u> which also includes radio waves, infrared rays, ultraviolet rays, X-rays, and secondary cosmic rays. Today, we understand that light has both particle and wave characteristics. The wave characteristics are most important for this minicourse.

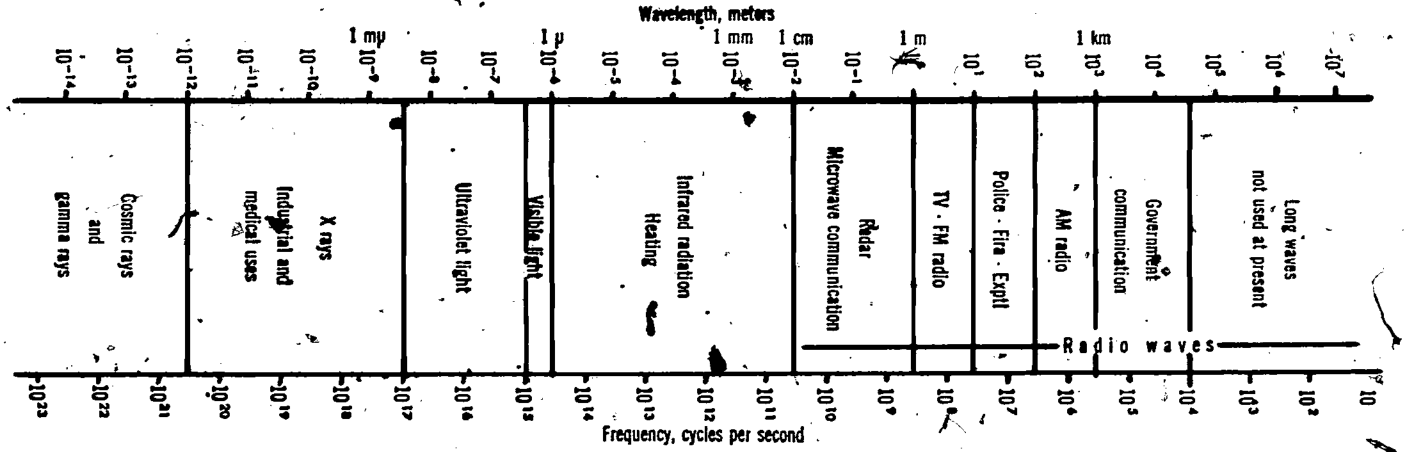
All parts (colors) of the electromagnetic spectrum have the same speed c in free space--2.998×10^8 meters per second, or 186,272 miles per second. These parts (colors) differ from each other in wavelength (λ) and in frequency (f).

A wavelength is the distance between any two corresponding points on a wave disturbance; a wave is a "disturbance" that has a regular, periodic, undulatory (waving) or vibratory characteristic. Two common parts of a water wave are the crest and the trough (See Figure 1). In electromagnetic waves, electric and magnetic energy parts have direction and size (magnitude) which correspond roughly to the crests and troughs of water waves.



A WATER WAVE
Fig. 1

Electromagnetic waves range from several hundred meters (miles) in length for radio waves, to extremely small cosmic waves (lengths much smaller than the eye can see). Light waves measure about 1/2,000,000 of a meter and occupy but a very, very small part of the electromagnetic spectrum (assortment of wavelengths). Figure 2 is a display of the various wavelengths associated with some common scientific wave classifications and some associated technical uses. These regions overlap and are therefore somewhat arbitrary designations.



ASSORTMENT (SPECTRUM) OF ELECTROMAGNETIC WAVES
Fig. 2

For example, infrared rays and ultraviolet rays overlap at the two visible ends of the light band. Both infrared and ultraviolet radiations are used in practical applications to photography and to fluorescence of materials. The largest visible light waves merge into the infrared, and the shortest light waves merge into the ultraviolet. In other words, the longest wavelengths we can see with the naked eye are red, and the shortest are violet.

It is customary to refer to the wavelength (λ) of light in terms of either the unit <u>nanometer</u> (nm), 10^{-9} meters, or the <u>Angstrom</u> (Å), 10^{-10} meters. The limits of the visible light spectrum are not precisely fixed because eye sensitivity is individual, as is hearing. For technical work, the limits of visibility are taken arbitrarily as the wavelength at which eye sensitivity has dropped to 1% of its maximum value. These limits are about 430 nm to 690 nm (4300 Å to 6900 Å). The eye can generally detect wavelengths beyond these if they are intense enough. The number of complete wavelengths (vibrations) per second that travel past any given point is a measure of wave <u>frequency</u> (f). The frequency of light is about 6×10^{14} waves (vibrations) per second. From the equation $c = f\lambda$, it can be shown that the frequency is equal to the speed of the wave motion (c) divided by the wavelength (λ), or $f = \frac{c}{\lambda}$.

Examination of this equation shows that the smaller the wavelength the larger the frequency; and, conversely, the larger the wavelength, the smaller the frequency. Wave energy is related to frequency and wavelength as follows: the higher the frequency, the greater the energy; or, the shorter the wavelength, the greater the energy. In other words, a basic unit * of blue light is more energetic than a basic unit of red light.

EXAMPLE 1: What is the frequency of light emitted by a sodium vapor lamp if the wavelength of the light is 5.0×10^{-7} cm in air?

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* The basic "unit" or "bundle" or "quantum" of light is called a <u>photon</u>.

SOLUTION:

$$c = 3.0 \times 10^{8} \text{ m/sec}$$

$$= 5.0 \times 10^{-5} \text{ cm} = 5 \times 10^{-7} \text{ m}$$

$$f = \frac{c}{\lambda}$$

$$= \frac{3.0 \times 10^{8} \text{ m/sec}}{5.0 \times 10^{-7} \text{ m}}$$

$$f = 0.6 \times 10^{15} \text{ cycles/second}$$

Often frequency is expressed in the unit Hertz (Hz); therefore, since one cycle/second = one Hertz (Hz), the calculated frequency is also,

$$f = 6.0 \times 10^{14} \text{ Hz}.$$

Do you see that cycles/sec and Hz represent the same units?

If exponential notation gives you trouble, refer to the minicourse "Metric System and Slide Rule".

EXAMPLE 2: What is the wavelength of light of the frequency 6.0×10^{14} Hz in meters?

GIVEN: $c = 3.0 \times 10^{8}$ m/sec

$f = 6.0 \times 10^{14}$ Hz

$= 6.0 \times 10^{14}$ cycles/sec

SOLUTION: $\lambda = \frac{c}{f}$

$$= \frac{3.0 \times 10^{8} \text{ m/sec}}{6.0 \times 10^{14} \text{ cycles/sec}}$$

$$= 0.5 \times 10^{-6} \text{ meters}$$

$$= 5.0 \times 10^{-7} \text{ meters}$$

It is informative to notice the units in $\lambda = \frac{c}{f}$:

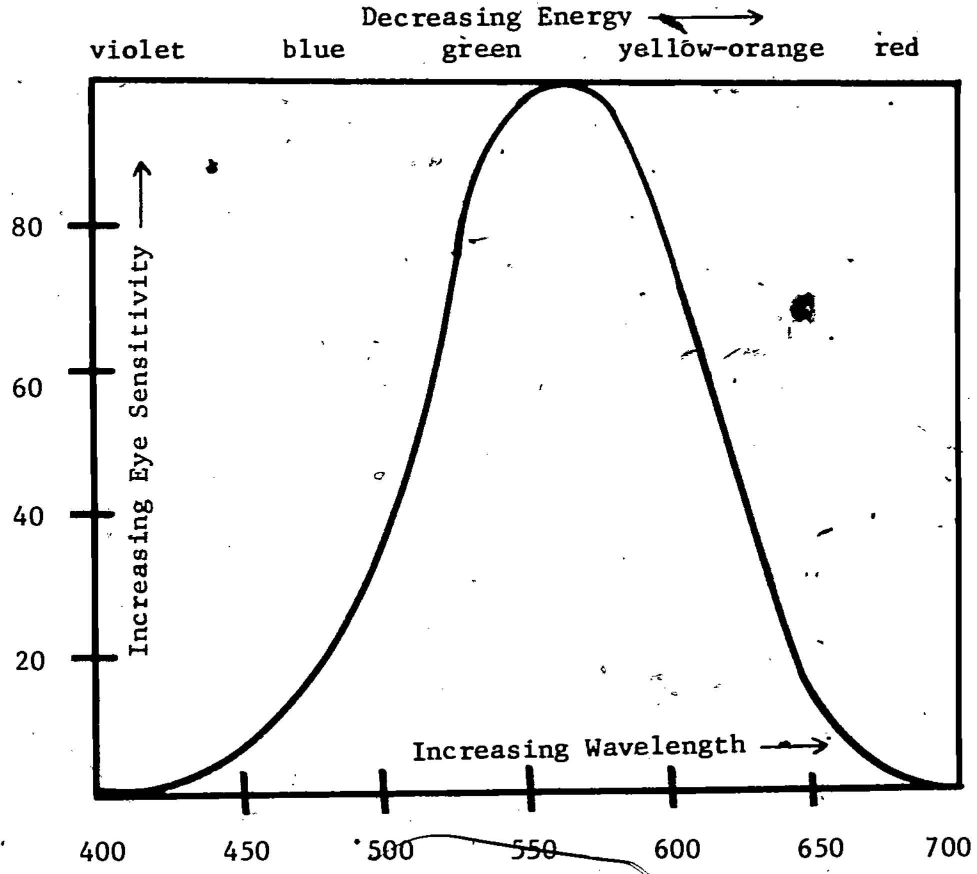
$$\frac{m/sec}{cycles/sec} = \frac{m}{sec} \div \frac{cycles}{sec} =$$

$$\frac{m}{sec} \times \frac{sec}{cycle} = \frac{m}{cycle} = m.$$

Since <u>cycles</u> are not <u>dimensional</u> units they are simply dropped from the final answer and the wavelength appears as meters (not as meters/cycle, $\frac{m}{cycle}$).

To summarize, visible light is part of the electromagnetic spectrum and lies between the ultraviolet and infrared spectral regions (bands). Like all frequencies of the electromagnetic spectrum, visible light travels at a speed of 2.998×10^8 meters/sec in a vacuum and obeys the mathematical relation $c = f\lambda$; in other words, all colors travel at the same speed in <u>free space</u> (vacuum) and all obey $c = f\lambda$.

Visible light differs from other wavelengths of electromagnetic energy because it can stimulate the optic nerves of the eye and trigger the phenomenon of seeing (vision). Figure 3 shows that the sensitivity of the average person to different colors of light radiation is in the region of about 555 nm. Figure 3 also shows that light of this wavelength produces a sensation of seeing yellow-green. Figure 3 also shows that light radiation having a wavelength just over 400 nm and just under 700 nm will be detected (seen) by the majority of people.



SENSITIVITY, ENERGY, AND WAVELENGTH
Fig. 3

<u>ACTIVITY</u>: Examine Figure 3. Why do you suppose that life rafts, police persons' coats, etc are manufactured in shades of yellow? Discuss the visibility of yellow tennis balls.

RESOURCE PACKAGE 1-2

SELF TEST

1) Name the man associated with each of the following:

   a) light as streams of tiny particles;

   b) light as a wave;

   c) light as a form of electromagnetic radiation.

2) What is the symbol for the speed of light, and what is its approximate numerical value in m/sec or mi/sec?

3) List the names of any four (4) of the of the "bands" or regions found in the electromagnetic spectrum.

4) Name the nearest bands (regions) found on each side of visible light in the electromagnetic spectrum.

5) What are the symbols for wavelength and frequency?

6) What unit is now officially used by scientists and technologists in place of cycles/sec?

7) Calculate the frequency of light of wavelength 6.6 x 10^{-5} cm in air (or in a vacuum).

8) What is the frequency of light of wavelength 5.4 x 10^{-5} cm in air (or in a vacuum).

9) The frequency of an X-ray is 3 x 10^{18} Hz. What is the wavelength of this ray in air (vacuum)?

10) Calculate the wavelength of light of frequency 7 x 10^{14} Hz in meters.

RESOURCE PACKAGE 1-3

ANSWERS TO SELF TEST

1) a) Newton
   b) Huygen
   c) Maxwell

2) $c = 3 \times 10^8$ m/s or $= 186{,}000$ mi/s.

3) Any four (4) of the following will do: radio waves, infrared, visible light, ultraviolet, X-rays, cosmic rays and gamma rays.

4) infrared and ultraviolet

5) wavelength - λ

   frequency - f

6) Hertz (Hz)

7) GIVEN: $c = 3 \times 10^8$ m/sec

$$= 6.6 \times 10^{-5} \text{ cm}$$

$$= 6.6 \times 10^{-7} \text{ m}$$

Therefore,

$$f = \frac{c}{\lambda} = \frac{3 \times 10^8 \text{ m/sec}}{6.6 \times 10^{-7} \text{ m}}$$

$$= 0.45 \times 10^{15} \text{ Hz}$$

$$= 4.5 \times 10^{14} \text{ Hz}$$

8) **GIVEN:** $c = 3 \times 10^8$ m/sec Therefore, $f = \frac{c}{\lambda} = \frac{3 \times 10^8 \text{ m/sec}}{5.4 \times 10^{-7} \text{ m}}$

$= 5.4 \times 10^{-5}$ cm $= .56 \times 10^{15}$ Hz

$= 5.4 \times 10^{-7}$ m $= 5.6 \times 10^{14}$ Hz

9) **GIVEN:** $c = 3 \times 10^8$ m/sec Therefore $\lambda = \frac{c}{f} = \frac{3 \times 10^8 \text{ m/sec}}{3 \times 10^{18} \text{ Hz}}$

$f = 3 \times 10^{18}$ Hz $= 1 \times 10^{-10}$ m

10) **GIVEN:** $c = 3.0 \times 10^8$ m/sec Therefore, $\lambda = \frac{c}{f} = \frac{3 \times 10^8 \text{ m/sec}}{7 \times 10^{14} \text{ Hz}}$

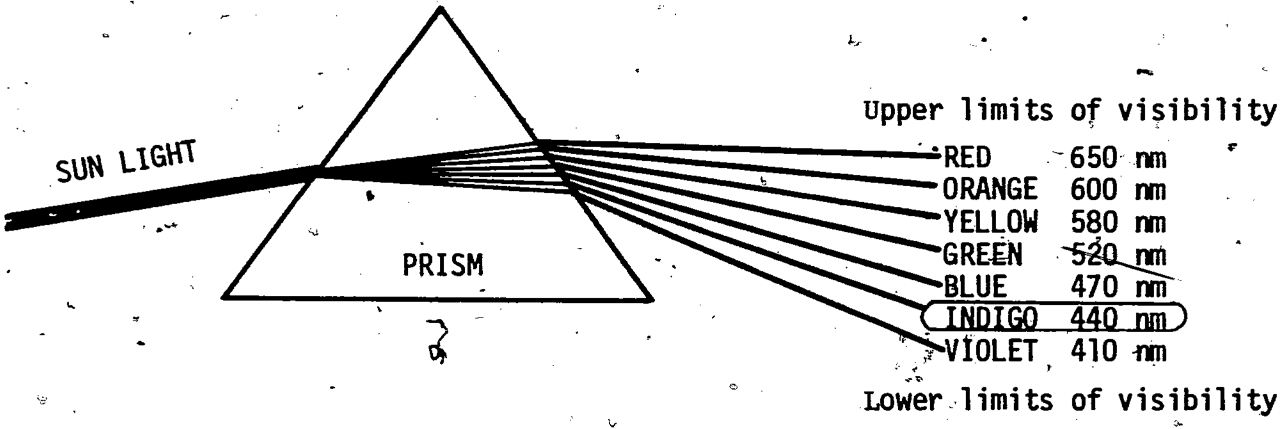
$f = 7 \times 10^{14}$ Hz $= 4.2 \times 10^{-7}$ m

RESOURCE PACKAGE 2-1

SPECTRUM I


Bausch and Lomb Optical Company

If you were to take a narrow beam of sunlight and pass it through a glass prism (see Figure 4), the light would be dispersed into a series of colored bands whose colors gradually blend into each other. This display of color bands is called a <u>solar spectrum</u>, and it was described over 300 years ago by Isaac Newton. Newton saw seven distinct colors--red, orange, yellow, green, blue, violet, and indigo; however, most people see only six, few persons (if any) being able to pick out indigo. Newton saw a spectrum in which the violet and other bands were spread out more than the red band. In fact, anyone viewing a spectrum produced by a glass prism will see the same dispersion, because the bending (refraction) of the violet light is greater as compared with the red light.



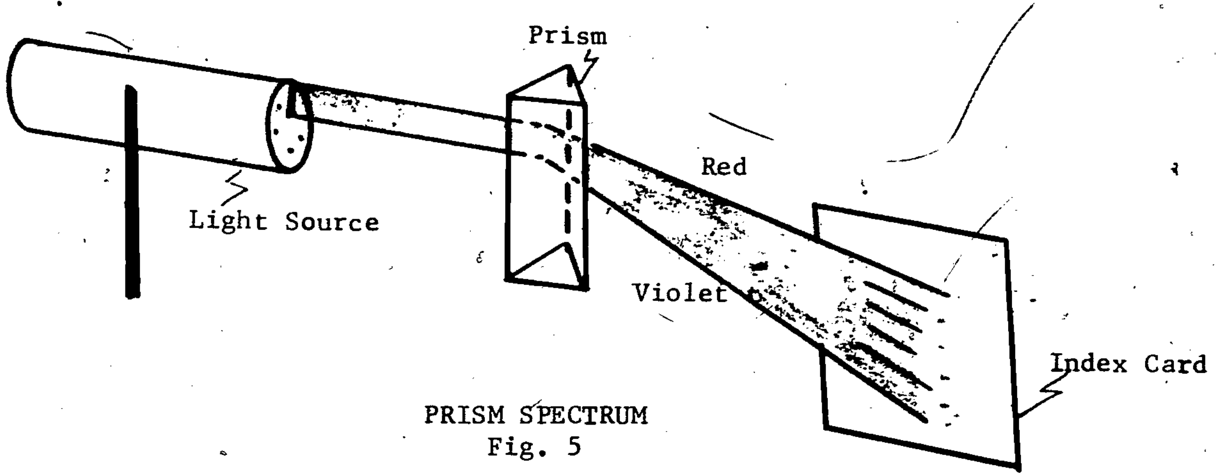
THE SOLAR SPECTRUM
Fig. 4

The spectrum is a good basis for studying the subject of color. A more complete description of the spectrum would require consideration of about 150 different spectral shades (colors), each just distinguishable from the next color. For simplicity, it is common practice to describe the spectrum of sunlight by means of the six colors mentioned on the previous page. In Figure 4, notice that these colors are arranged according to their wavelength, from shortest to longest; i.e., from violet to red. Figure 4 also gives the approximate wavelengths of the spectral waves which correspond to the six predominant colors.

Now try the following investigation:

<u>Materials Needed:</u> light source with a slit about 3 mm wide
glass prism
transmission grating
large white index card or similar paper

Arrange the light source, prism, and index card in such a manner as to produce a spectrum on the index card (see Figure 5).

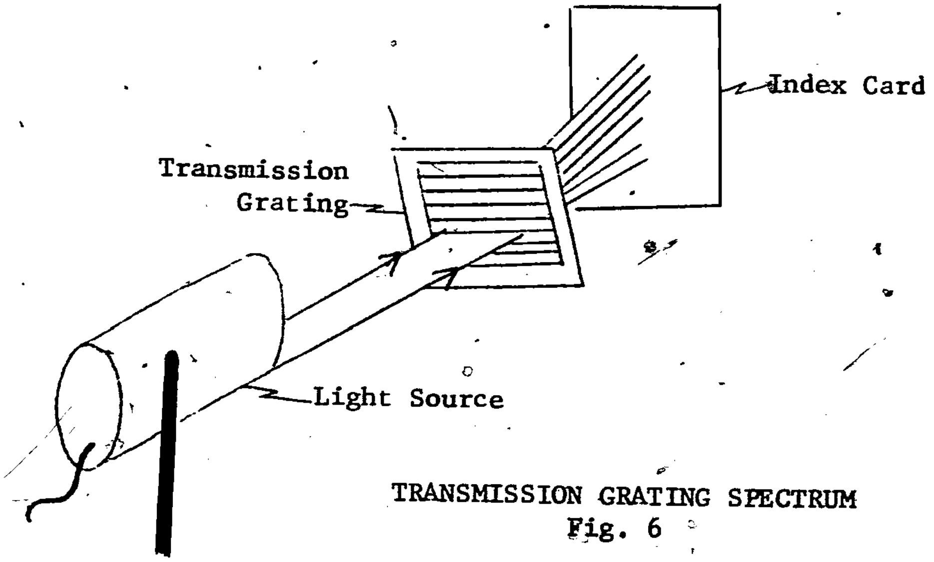


PRISM SPECTRUM
Fig. 5

List the colors you see in the spectrum. Name the three colors that are the brightest.

Replace the prism with the <u>transmission grating</u> in the arrangement of Figure 6, to produce a spectrum.

When light passes through a series of tiny, parallel slits, a spectrum is displayed.



TRANSMISSION GRATING SPECTRUM
Fig. 6

Make a sketch of the two different spectra, using either colored pencils or crayons.

How does the spectrum produced by the prism compare with the spectrum produced by the diffraction grating (there is a fundamental difference!).

RESOURCE PACKAGE 2-2

SPECTRUM II

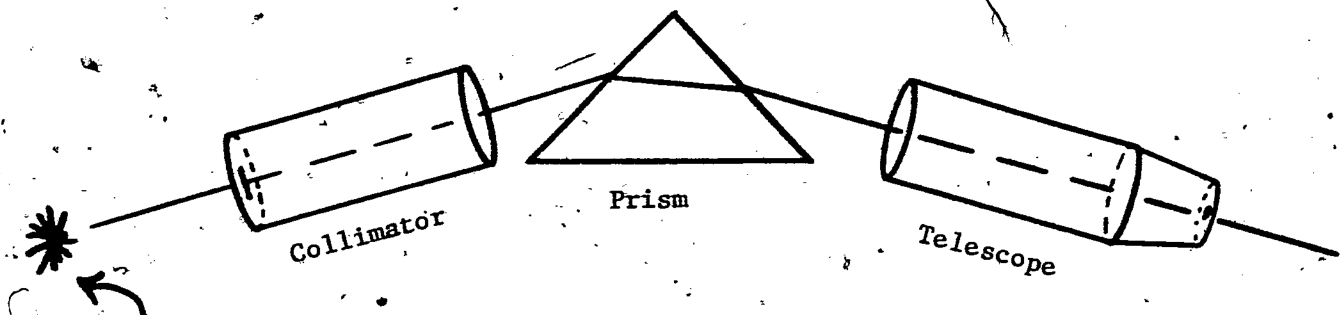
Illumination from different light sources--fluorescent, mercury vapor, sodium vapor, etc. produces different spectra, with each spectrum unique for a given kind of source, just as fingerprints are unique for an individual. It is common practice for people in the textile, billboard and decorating business to consider the appearance of their wares under different lighting; because material seen under one type of light source may appear a different color or shade of color when viewed under different types of lighting.

<u>Investigation:</u> To look at the spectra produced by different types of light sources, you can use the following:

- a spectroscope
- an incandescent lamp
- a mercury vapor tube
- a sodium vapor tube
- a neon vapor tube
- a regular fluorescent light
- a fluorescent light for greenhouses (plants)
- an induction coil
- a power supply
- a support for the discharge tube

A <u>spectroscope</u> is an instrument for producing and viewing spectra. The term spectroscope and <u>spectrometer</u> both refer to the same type of instrument, with some preference for the term spectrometer if the light wavelength is measurable from a scale on the instrument.

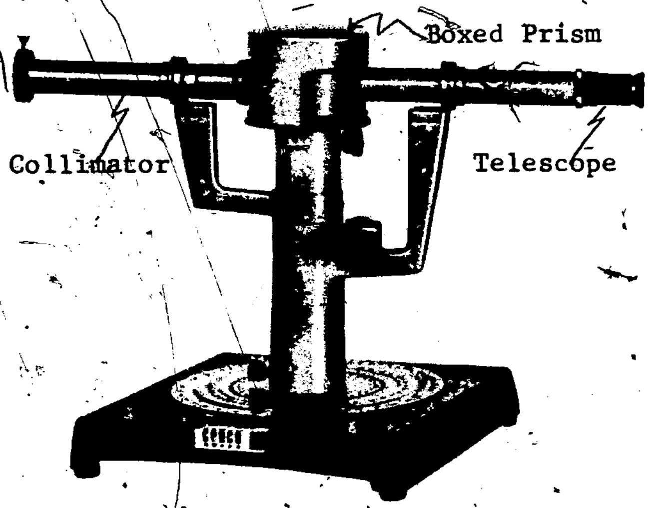
One simple form of spectroscope is shown below, in Figure 7. There are essentially three parts: a collimator, a prism and a telescope. The collimator is the tube which reduces the light to a small beam directed into the prism. The light beam passes through the prism and is focused to form an image at the telescope.



SPECTROSCOPE
Fig. 7

Set up a spectroscope or spectrometer and practice by viewing the solar spectrum; some other light source will do, of course. Adjust the image of the spectrum until it is horizontal, clear and sharp.

It may be necessary to make an enclosure for viewing different light sources. One similar to the one shown in Figure 8 can be constructed from a cardboard box. The enclosure will reduce unwanted light



SPECTROSCOPE
Fig. 8

from outside sources. The enclosure can also be painted a flat (non-reflective) black inside for further use in this minicourse.

Observe many different light sources. While viewing each spectrum, make a drawing <u>with colored pencils or crayons</u> of the spectrum in a table similar to the one in Figure 9, below.

SOURCE	COLOR					
	Violet	Blue	Green	Yellow	Orange	Red

SPECTRAL TABLE
Fig. 9

If you are able to do so, view sunlight at around midday and then again in the late afternoon just as the sun is going down. Can you see if there is a difference in the spectra?

Sodium vapor and mercury vapor lamps are sometimes used in road and street lighting. Surely you have noticed the difference in the appearance of colored materials when under these different lights? Does your Table of Spectra (Figure 9) give you any ideas about these differences?

It should be noted that each element has its own distinguishing spectrum. You could consider it a fingerprint by which one may recognize an element. This is a way that astrophysicists can tell what a star is made of, without ever even touching a star!

Investigation: Try heating some sodium chloride (table salt) in a flame. You should see an intense yellow color; view this color through your spectroscope. If your lab has any chloride salts of potassium, of copper, of calcium, of barium and/or strontium, try these salts also. Do you see any similarity between any of these colors and the colors in fireworks? Which ones appear similar?

RESOURCE PACKAGE 2-3

MEASURING WAVELENGTHS OF COLORS

MATERIALS:

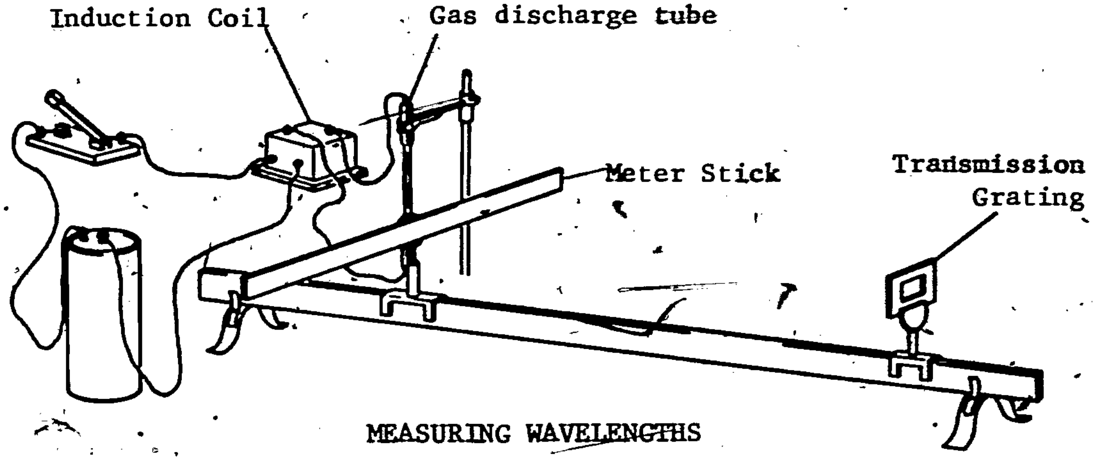
You will need the following:

- transmission diffraction grating
- support for grating
- two meter sticks
- induction coil
- neon or other discharge tube
- power supply (6 volt DC)
- supports for meter stick

PRODUCTION:

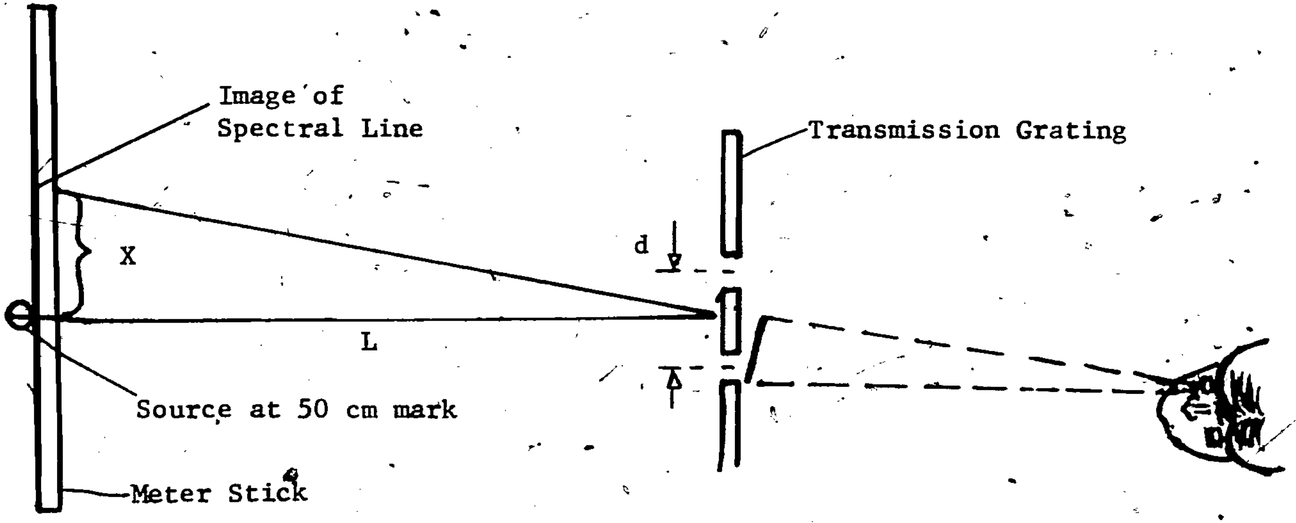
Arrange the equipment as shown in Figure 10, below.

As light strikes a diffraction grating, it is bent (diffracted) by the slits in the grating. As you look through the grating, you will see the image of the spectrum of the source light positioned both to the right and to the left of the actual position of the source. For each different source light there will be several different lines of different colors; but each kind of source will have identical lines and colors ("light fingerprints"). Notice in Figure 11 that the geometry of the arrangement utilizes the apparent position of the imaged lines.



MEASURING WAVELENGTHS
Fig. 10

Be sure that your light source is vertical and fastened against the 50 cm mark on the meter stick. The distance along the meter stick from the grating to the source is labelled L. For convenience, choose a distance L that is an even value, such as 60 cm or 80 cm. Record the value of L in a table similar to Table 1, Figure 12.



GEOMETRY FOR MEASURING WAVELENGTH
Fig. 11

To measure X, have someone move a ruler along the back side of the meter stick until it is in back of the line image you are observing while looking through the grating. The distance between the 50-cm mark and the position of the line will be X. Record this value on your table.

Your instructor will give you the value for the distance between the grating slits. It can be shown from trigonometry and the geometry of similar triangles, that the wavelength can be calculated using the formula:

$\lambda = d \sin \theta$. *

TABLE 1

				d =		
Color of Line	X (cm)	L (cm)	$\tan \theta = \frac{X}{L}$	Angle θ (^{o})	Sin θ	Wavelength $\lambda = d \sin \theta$ (cm)

DATA TABLE
Fig. 12

---

* Have your teacher refer you to Sections of an appropriate minicourse if you need help understanding the trigonometry of sin θ and tan θ.

Calculate the frequency (f) of the light waves for each calculated wavelength. Use the equation, $c = f\lambda$, where c is the speed of light, 3.0×10^{10} cm/sec. From your calculations, which colors have the longest wavelengths? Which colors have the shortest wavelengths?

RESOURCE PACKAGE 2-4.1

SELF-TEST

1) Name, in order, the six (6) major colors found in a solar spectrum, starting with the color having the longest wavelength.

2) Give the approximate wavelength for each of the colors named in Question 1.

3) What colors were seen in a mercury spectrum? sodium spectrum? neon spectrum?

4) How does a fluorescent spectrum appear to differ from other spectra (Hint: Consider brightness; i.e. intensity of the colors)?

RESOURCE PACKAGE 2-4.2

ANSWERS TO SELF-TEST

1) Red, orange, yellow, green, blue and violet.

2) Red, 620-700 nm; orange, 590-620 nm; yellow 570-590 nm; green, 500-570 nm; blue, 450-500 nm; and violet, 400-450 nm.

3) mercury - red, yellow, green, blue and violet.

   sodium - yellow.

   neon - green, yellow and red.

4) Blue, orange and red stand out more in the spectrum of fluorescent lighting.

RESOURCE PACKAGE ~~3-1~~

COLOR TEMPERATURE

A simple means of measuring or indicating intensity differences in a continuous* spectrum is needed because of the variation of possible colors, shades and intensities. Such a means of indicating spectral intensity differences is especially important in careers involving color photography and color reproductions. One way of measuring spectral intensity is known as measuring the color temperature.

If a piece of iron is heated from room temperature until it is white hot, a noticeable change in color occurs as the temperature of the iron reaches higher and higher values. First, the iron will turn dull red; and as the temperature increases, the glow will change to bright orange, then to yellow and finally to "white hot". This transition in color with temperature is closely related to the definition of color temperature. That is, if you take a black object that completely absorbs all light falling upon it (known as a black body), and heat the black body to incandescence (incandescence is the emission of light because something has been heated), you would observe a continued change in the spectrum produced by the heated object as the temperature increased.

The color temperature of a light source is determined by comparing its spectral intensity to a similar spectrum produced by a black body. When the two spectra are matched, the temperature of the black body

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* A continuous spectrum has no "breaks" or dark lines dividing its color bands; when such lines exist between color bands, the spectrum is called a line spectrum. If you are curious, you will find that there are two kinds of line spectra: emission spectrum and absorption spectrum.

is assigned as the color temperature of the light source. For example, to find the color temperature of a 500-watt photoflood lamp, you would heat a black body until its spectrum intensity matched that of the lamp. When the two spectra are matched, the temperature of the black body would be assigned as the color temperature of the photoflood lamp; and such temperatures are usually expressed in degrees Kelvin (K). Remember, Kelvin temperature is obtained by adding 273 to the temperature in degrees Celsius (C). Thus, 3,000 °K, the color temperature of a "warm white" fluorescent light, is equal to 3,000 - 273, or 2727 °C.

Color temperature is only associated with objects that emit light; and it should be remembered when referring to the color temperature of a light source, one is referring to the temperature of a black body, not the temperature of the light source.

Color temperatures of some common light sources are listed below:

Source	Color Temperature (°K)
Sunlight	5400
Skylight	1200 to 1800
Photographic Daylight	5500
Carbon Arc, White Flame	5000
Flashcube or Magicube	4950
Clear Zirconium Foil-filled Flash	4200
Clear Aluminum Foil-filled Flash	3800
500-watt (Photoflood)	3400
500-watt (3200 °K photographic)	3200
200-watt (General Service)	2980
100-watt (General Service)	2900
75-watt (General Service)	2820
40-watt (General Service)	2650

Color temperatures are chiefly applied to sources giving a continuous spectrum. Can you name some light sources that do not have a continuous spectrum (Hint: You have already encountered some in this minicourse.)?

Using a spectroscope, view the spectra produced by several ordinary light bulbs--200-watt, 100-watt, 75-watt, 60-watt, 40-watt, etc. You should view these light sources in the box used for viewing the discharge tubes in Resource Package 2-2. Keep each different bulb the same distance from the spectroscope for each viewing. What do you notice about the spectra as the wattage decreases?

Color temperatures are of considerable technical use. The photographic industry produces color films that give true color only from light of a specific color temperature. Thus, photographers who are concerned about exact color reproductions have to be certain about the color temperatures produced by the lighting (illumination) of the subject.

ACTIVITY:

Listed below are some different types of available color film. Find the type of illumination and color temperature for which each film is designed. Your teacher will refer you to suitable referencs; also, useful sources for such information:

Type	Illumination Needed	Color Temperature (^{o}K)
Kodachrome X		
Kodachrome 25		
Kodachrome 64		
Hi-Speed Ektachrome (2 types)		
Fujichrome		
Agfachrome		
Anscochrome		
Kodacolor X		
Ektacolor		
Agfacolor		
Fujicolor		
CPS		
Anscolor		

When you complete the chart above, you should be convinced that color films require specific light sources and color temperatures. If you use a color film with its recommended light source, you can expect pictures or slides to give a good color reproduction of the actual scene (if nothing else goes wrong). However, if correct lighting is not available, you have the following four choices: (1) change film, (2) use a <u>color compensating filter</u>, (3) take the picture and hope for the best, or (4) read a good book. A color compensating filter is one of the better choices, although there are some good books to be read these days.

A color compensating filter changes the source of illumination color temperature to match the color temperature for which the film is designed. For example, if you use a flood lamp with daylight film and are interested in getting true color reproduction, you would need to correct the color temperature of the floodlight (3400 ^{o}K) to that of daylight (5500 ^{o}K) by the use of an appropriate color compensating filter. Again, remember that you are not making the floodlight hotter; you are changing the spectral composition of the light reaching the film.

How do you determine the correct compensating filter? One way to determine the correct filter for changing the color temperature of a light source is to use the "Mired System for Light Source Conversion." This system assigns a numerical value, called a <u>mired</u> (micro-reciprocal degrees) value, for each color temperature.

$$\text{Mired Value} = \frac{1{,}000{,}000}{\text{Color Temperature in } ^{o}\text{K}}$$

The mired value for a given color temperature (^{o}K) can be located in Figure 13. For example, if the color temperature is 3400, you would locate 3000 in the left-hand column, go across until you are under 400, and find the number 294. This is the mired value for 3400 °K.

MIRED VALUES OF COLOR TEMPERATURES FROM 2000-6900 °K

°K	0	100	200	300	400	500	600	700	800	900
2000	500	476	455	435	417	400	385	370	357	345
3000	333	323	312	303	294	286	278	270	263	256
4000	250	244	238	233	227	222	217	213	208	204
5000	200	196	192	189	185	182	179	175	172	169
6000	167	164	161	159	156	154	152	149	147	145

MIRED VALUES
Fig. 13

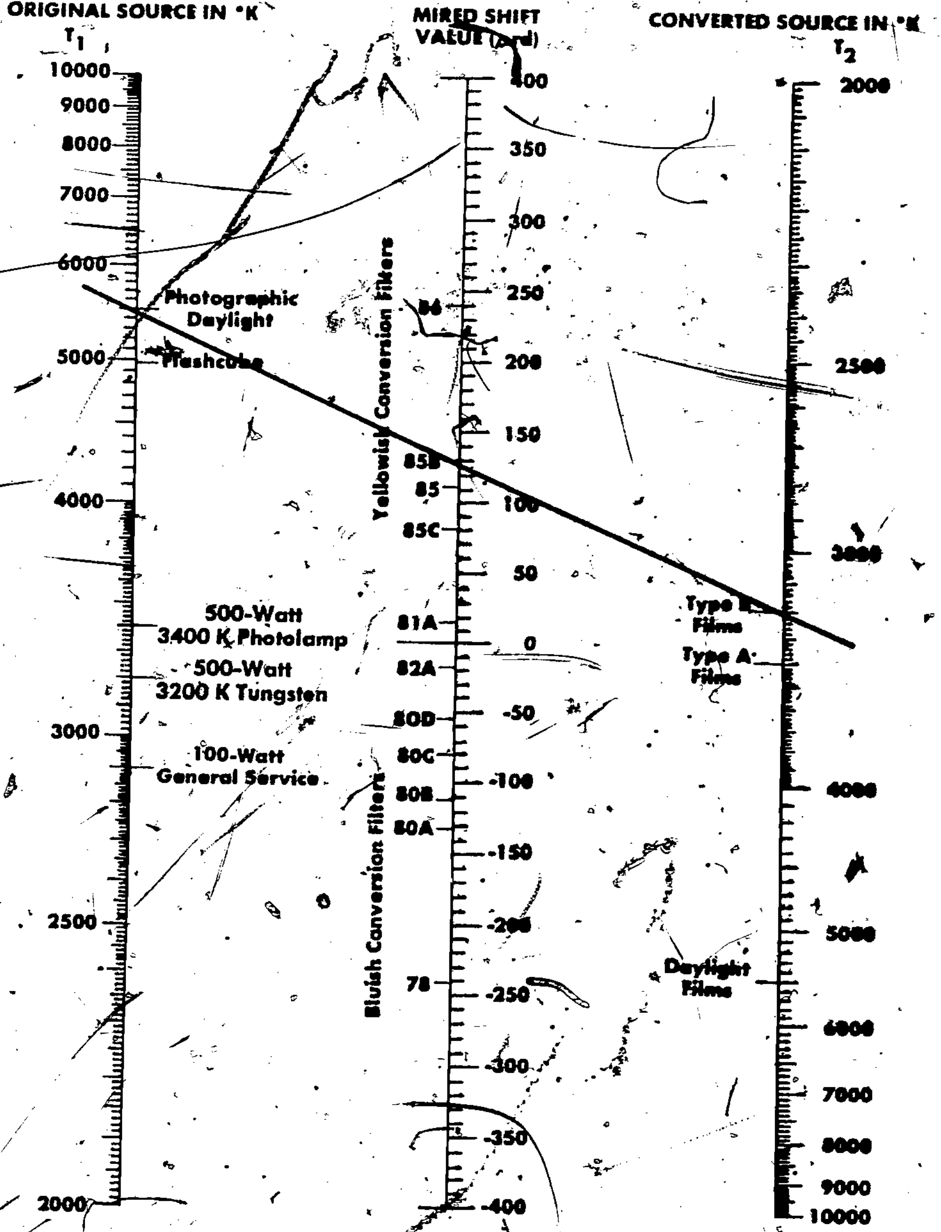
Each color filter available is given a <u>mired shift value</u>, which is represented by the expression,

$$\left(\frac{1}{T_2} - \frac{1}{T_1}\right) \times 10^6,$$

where T_1 is the color temperature of the original light source and T_2 is the second light source color temperature. A simpler expression, in terms of mired values, is $M_2 - M_1$, where M_1 is the mired value for the first light source and M_2 is the mired value for the second light source. Thus, if the mired values are known, they can be used to determine which color filter to use. In the expression, $M_2 - M_1$, the mired values are assigned either a positive or negative value, depending upon the color of filter.

Yellow filters are assigned a positive mired shift value, corresponding to a lowering of the color temperature and resulting in an increase of the mired number for the original light source. Blue filters have the opposite effect. They are assigned a negative shift value, corresponding to a raising of the color temperature and resulting in a reduction of the mired value.

Another means of determining the correct filter is by using a mired nomograph (see Fig. 14). The nomograph makes it easy to select the correct filter when the color temperatures of the original and the converted sources are known (see Fig. 14). To find the correct mired shift value, place one side of a straight edge on the point on the left-hand vertical line corresponding to the color temperature of the available light source, T_1, and place the other edge on the color temperature point-



MIRED NOMOGRAPH FOR LIGHT SOURCE CONVERSION
Fig. 14

of the desired source, on the right-hand vertical line, T_2. The point on the center vertical line where the straight edge crosses indicates the mired shift value for the filter. Notice that the zero (0) point requires no filter, the positive values above zero (+) require yellow filters, and the negative values below zero (-) require blue filters.

Sometimes filters are combined to obtain the correct mired shift values. The correct combination of filters can be calculated by adding the mired shift values for each individual filter in a given combination.

It is of importance to note that the use of filters raises the problem of correct exposure, because any colored filter placed in front of a camera lens reduces the amount of light passing through the lens and reaching the film. Therefore, an increase in exposure time or <u>f-stop</u>* is required when a filter is used. Figure 15 gives a list of different types of filters, of corresponding exposure increases, and of mired shift values.

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* See the minicourse, <u>Photography</u>, for an explanation of f-stop and other photographic terms.

Filter Color	Filter Number	Approx. f-stop Increase	Mired Shift Value
BLUE	80A	2	-131
	80B	1-2/3	-112
	80C	1	-81
	80D	1/3	-56
AMBER (YELLOW)	85C	1/3	81
	85	2/3	112
	85N3	1-2/3	112
	85N6	2-2/3	112
	85N9	3-2/3	112
	85B	2/3	131
	85BN3	1-2/3	131
	85BN6	2-2/3	131

FILTERS AND MIRED VALUES

Fig. 15

SELF-TEST

I. Determine the mired values for the following color temperatures, using Figure 13.

1. 3300 °K
2. 4700 °K
3. 2100 °K
4. 6800 °K
5. 5500 °K

II. Using 5500 °K as the color temperature desired (T_2) and one of the temperatures in Problem I, above, as the original light source (T_1), determine the mired shift value. Check your calculation by using the nomograph in Figure 14. Use both of these methods to calculate the shift value:

$$\left(\frac{1}{T_2} - \frac{1}{T_1}\right) \times 10^6 \text{; and } M_2 - M_1.$$

III. In terms of the sign obtained in Problem II, what general color filter (yellow or blue) should you select?

IV. Listed are some common temperature changes; i.e., from source temperature to desired temperature. The first temperature is T_1, and the second is T_2. Determine the mired shift value for each problem. Then refer to the conversion filter chart (see Figure 15) and determine the filter that should be used:

1. 3200 °K to 5500 °K
2. 4200 °K to 5500 °K
3. 5500 °K to 3400 °K
4. 3800 °K to 5500 °K
5. 5500 °K to 3200 °K

ANSWERS TO SELF-TEST

I.

1. 303
2. 213
3. 476
4. 147
5. 182

II. Using $M_2 - M_1$, where $M_2 = 182$ and M_1 are the values in section I.

1. 182 - 303 = -121
2. 182 - 213 = -31
3. 182 - 476 = -294
4. 182 - 147 = 35
5. 182 - 182 = 0

III.

1. Blue
2. Blue
3. Blue
4. Yellow
5. No filter necessary

IV.

1. -131, 80A
2. -56, 80B
3. 112; 85, 85N3, 85N6 or 85N9
4. -81, 80C
5. 131; 85B, 85BN3 or 85BN6

RESOURCE PACKAGE 4-1

PROPERTIES OF COLORED MATERIALS

What factors determine color? Why do you see a particular color from materials such as pigments, dyes, paints, printing inks, colored liquids, crystals, glass, fabrics, flowers, leaves, skin, hair, fur, etc.? Factors that determine color are of great importance in many occupations, one of which you could well be working at some day.

The color of an opaque* object is made visible by the light reflected from it. Look through a transparent material, such as colored glass, we see its color by means of the light transmitted through it. Materials also absorb light; that is, a portion of the light energy that strikes the material remains trapped by that material. Transmission, absorption and reflection are all involved in an understanding of the colors of objects.

Objects that appear black do so because they are not emitting light and they are absorbing most of the incident light upon them. They appear black due to the contrast between them and all of the light that surrounds them. Black materials do not absorb all of the incident light. For example, the blackest

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*Opaque means light cannot pass through the object. Window glass is transparent (light readily passes); certain shower doors are translucent (light passes poorly and objects cannot be clearly seen); and a wooden door is opaque (light cannot pass through it).

material , black velvet, reflects at least 3% of the incident visible light. Similarly, objects appear white because they are emitting light and/or reflecting most of the incident light; and just as materials that appear black do not absorb all incident light, neither do materials that appear white reflect all of the incident light. For example, even the whitest material, freshly-fallen snow, absorbs 3-5% of the visible incident light, reflecting about 95-97% of the incident light.

As you can see from your surroundings, there are degrees of whiteness and degrees of blackness. If you were employed in the paper industry, you might have a job in quality control and be concerned with the whiteness of different types of paper. In the paper industry, it is necessary to have standards to measure the reflectivity of white or near-white surfaces. Without such controls, a company might produce a package of typing paper of one whiteness one day and another whiteness the next.

Of course, besides whiteness and blackness, materials of different colors exist. Materials are of a certain color because they absorb more light from certain parts of the spectrum than from other parts. A red opaque object may appear red because it absorbs most of the violet, blue, green and yellow light, and reflects most of the red light. A red glass (transparent object) may appear red because it transmits mostly red light, and absorbs or reflects most of the violet, blue, green and yellow light. An oversimplification would be to say that colored materials reflect or transmit only the light of its apparent color and absorb all the light from the other colors. This is an oversimplification because no colored material reflects or transmits all of the light of one color. An important property of colored materials is that they reflect or transmit or absorb a <u>mixture</u> of various colors, even though some of these colors may occur only in tiny amounts.

Obtain a set of color filters from your instructor; they may be labelled red, green, blue, yellow, magenta*, and cyan*. Of course, any colored transparent material will do (if you do not have a standard filter set). Place a yellow filter in front of a light source. Look through the filter and at the light source. What is the color of the beam after it passes through the filter? Now place a red filter in front of the yellow filter. What is the color of the light now? Replace the red filter with a green filter. Did you notice that the yellow light contains both red and green light? This question relates to the over-simplified statements mentioned above.

INVESTIGATION I:

Now you are to investigate what happens to white light when it passes through transparent colored materials. Set up a spectroscope or spectrometer so that you can see an ordinary white light spectrum. Place a red filter between the light source and the collimator. Look at the spectrum and note which color bands are blocked and which color band(s) are passed. This can be done by moving the filter back and forth in front of the collimator. Write your observations in a chart similar to Figure 16 (use a piece

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* Look up definitions of these two terms (They are defined and used later in this minicourse, but it is recommended you use an "outside" definition to start with).

of your paper; please don't write in the minicourse):

COLOR OF FILTER	COLOR BAND(S) PASSED	COLOR BAND(S) BLOCKED
RED		
GREEN		
BLUE		
YELLOW		
CYAN (BLUE-GREEN)		
MAGENTA (RED-BLUE)		

FILTER EFFECTS
Fig. 16

Now, let us find out what happens to a spectrum when you hold two filters of different colors in front of the collimator of the spectroscope. Before using the filters, examine the chart (Figure 16) and write down your prediction as to which color band(s) will pass through (a) red and green filters, (b) red and blue filters and (c) blue and green filters. Write your predictions into a chart, such as shown in Figure 17. (Again, draw a chart on your own paper.) After you have written your predictions, hold the respective pairs of filters together in front of the collimator and observe the color you see in the spectroscope. Write down these observations in the chart, Figure 17. Compare your predictions and your observations and try to understand what is happening.

COLOR OF FILTERS	COLOR SEEN	
	PREDICTIONS	OBSERVATIONS
RED AND GREEN		
RED AND BLUE		
GREEN AND BLUE		

PAIRED FILTER EFFECTS
Fig. 17

Specifically, what happened to the colors in the white light spectrum when it was passed through each pair of color filters listed in Figure 17?

Next, repeat these procedures for the colored filter pairs in Figure 18.

COLOR OF FILTERS	COLOR SEEN	
	PREDICTIONS	OBSERVATIONS
YELLOW AND CYAN		
YELLOW AND MAGENTA		
CYAN AND MAGENTA		

PAIRED FILTER EFFECT
Fig. 18

Based upon all these observations, do transparent colored materials add or subtract color from light passing through them?

INVESTIGATION II:

What happens when white light strikes a colored surface? You will need construction paper of the following colors: red, blue, cyan, black, green, yellow, and magenta. You will also need a white light source and a spectroscope or spectrometer. Arrange the light source so that light reflects off the paper and into the collimator of the spectroscope. Make a chart similar to Figure 19. One at a time, reflect white light off the surface of each card in the first vertical column (red, then orange, then yellow, etc.). For each card, make a check in the row corresponding to the brightest color seen in the spectrum from white light reflected off the card. For example, the third card on which the white light is reflected is yellow(3rd row down); therefore, on the horizontal row (3rd row) to the right of the word yellow, you will mark the box below the color in the spectrum which seems brightest.

COLOR OF SURFACE	SPECTRUM COLORS					
	RED	ORANGE	YELLOW	GREEN	BLUE	VIOLET
RED						
ORANGE						
YELLOW						
GREEN						
BLUE						
CYAN						
MAGENTA						
BLACK						

BRIGHTNESS OF REFLECTED COLORS
Fig. 19

Based upon Investigations I and II, would you say that the apparent color of a material usually is the brightest one in the mixture of wavelengths (colors) reflected or transmitted by the material?

Your data indicates that the predominant (brightest) wavelength of a red material is red; a green material reflects (transmits) more green, and so on. Also, that certain materials have several dominant (bright) wavelengths (colors), like magenta and cyan. Figure 19 should show that magenta reflects more blue and red light. If you have a magenta dye or pigment, you could change the color by adding more of one of the predominant colors; that is, you could increase the proportion of blue light over red light and produce a more purple or violet dye or pigment. The increased proportion of blue over red would place the dye in a certain <u>hue</u>. Hue is a technical term for describing colors. Hue separates one color group from the next, and it labels whether the color appears red, green, orange, yellow, blue, etc. The term hue is not limited to the six basic colors, but includes the basic colors and variations in these colors.

Yellow is the exception to the predominating wavelength statement about color determination. As you should be able to see from your charts of Figures 16 and 19, yellow materials absorb violet and most of the blue from white illumination and reflect (if opaque) and transmit (if transparent) the green, yellow and red rays. Also, you may have noticed that the yellow band is smaller than the red and green bands. If you look at yellow color through your spectroscope, you should see that the total quantity of red and green appears to far exceed that of yellow.

The question may now arise, "How does this apparently small amount of yellow light dominate the large quantity of red and green?" The answer to this question is that the <u>mixture</u> of red light and green light produces a visual sensation of seeing yellowness; so in other words, the red and green reflected (transmitted) by a yellow material adds to the basic yellow optic sensation caused by the genuine yellow wavelengths. The eyes sees an equal mixture of red and green as yellow color.

In studying color, one can consider the quantity of colored light coming from a material. Obviously, the quantity of color transmitted or reflected by a surface is not only characteristic of the material itself but depends also upon the intensity of the light reaching the material.

One characteristic property of colored materials is the proportion of incident light which reflectes from their surfaces. As you have already read, a white surface does not reflect all light, and a black surface does not absorb all light. Likewise, no colored material reflects or transmits all of the incident light of its own color; therefore, the light absorbed by the color of the material results in a loss of brilliance. For example, consider the spectrum produced by most green materials. Besides absorbing most of the red and violet light falling upon them, green materials also absorb a considerable amount of the blue, green, yellow and orange light. Consequently, most green materials are dull and dark in appearance.

Yellow and red substances usually reflect or transmit between 70% and 80% of the wavelengths in the yellow, orange and red regions. Thus, it can be seen that, under the same set of conditions, the amount of colored light reflected by violet, blue and green substances is usually less than the amount of light reflected by materials of a yellow, orange or red color. Could this be a logical explanation as to why yellow or orange colors appear to be brighter?

Based upon your investigations, would you say that it is the longer wavelengths or the shorter wavelengths that are more reflective?

The intensity of the visual sensation produced by a colored surface is termed <u>lightness</u> or <u>brightness</u>. <u>Lightness</u> is proportional to the amount of light reflected from a surface, and the term is another way of saying how <u>brilliant</u> a color appears. For example, a cherry red color has a greater lightness quality than a dark red color.

Take several crayons of different lightnesses of red (pink, carnation pink, salmon, red, maroon, brick red). Color a 3 x 5 index card with each color. Arrange the colors according to lightness. Now view the spectrum of reflected light from each color. Do the spectra appear to differ in brilliance? Later on, lightness will be related to the word <u>tint</u>.

As you have seen, none of the color components of white light are completely absorbed by colored materials and a certain amount of the white light is reflected, unchanged. This white light reflection varies with different materials. The unchanged white light that is reflected will mix with the reflected color rays and the mixture will tend to produce a <u>tint</u> of that color. For example, many colored materials reflect only about 10% of white light, which is negligible when compared with the predominate wavelength (color) reflected. Consider the case of a certain yellow pigment which reflects 90% of the red, orange and yellow light and about 90% of the green light, but only 10% of the violet and blue light. It turns out that if you take the 10% of the blue and violet light reflected by this yellow pigment, and mix it with the respective 10% of the overall yellow, red, orange and green light reflected, then the overall product mix reflected will be: 10% unchanged white light, 10% white light from the 10% mix, and 80% yellow light.

To reinterate, the yellow pigment is reflecting an effective yellow consisting of about 80% of the red, orange, yellow, and green light plus 10% of the unchanged white light, 10 % white light from the mix. Obviously, the more white light that is reflected, the more pale a material will appear. In the case of the yellow pigment discussed above, how would you produce a paler yellow?

Since the reflection of unchanged white light is a surface effect, an increase in surface area, without corresponding increase in pigment, should increase the proportion of white light reflected from the colored material.

INVESTIGATION:

Take a large crystal of copper sulfate and record its color. Place this crystal in a mortar and grind it into fine powder. Record the color of the powder. Is the copper sulfate color the same as it was before you ground it? Write down your answer.

Now, add several drops of water to the powdered copper sulfate. Do you observe any color change? Record a possible explanation for your answer.

The effect of the scattering of light upon color has to be taken into account by the colorist in the textile industry: scattering is changing the direction of a stream of light by reflecting it off a many-angled, uneven surface. For example, scattering effects result from the different fiber sizes in fabrics. The finer the fabric, the more the color of the fabric is diluted from the original dye color when white light is reflected from it.

In general, the smaller the proportion of white light reflected from a colored material, the less the tint or the more colorful the fabric. In other words, the more the colored rays dominate the reflected spectrum, the less the tint or the more colorful is the fabric.

The term saturation is also used for the description of colors. Saturation refers to the extent to which the dominant wavelength predominates over other spectral wavelengths, or the degree (percent) to which the colored rays exceed the "diluting" white rays. Saturation can also be thought of as the "strength" of the color, or how much of a spectrum is color and how much of a spectrum is white light. A red material is said to be more saturated than a pink material; a pink material could be said to be a tint of a more colored (saturated) material; and the hue of the material would be represented by the words red or pink, or whatever the case might be.

INFLUENCE OF ILLUMINATION UPON COLOR:

'Yes,' I answered you last night;
  'No,' this morning, sir, I say.
Colors seen by candlelight
  Will not look the same by day.*

---

*From "The Lady's Yes," by Elizabeth Barrett Browning.

Thus far in the minicourse, we have been talking about the properties of colored materials that have been inlluminated by daylight or white light. Remember that color is not the same kind of property of a material as is size, chemical composition and the like. A material's color results from its ability to absorb, reflect, produce, or transmit light rays. If an object emits light (color) it is said to be luminous. If an object is not luminous, then it can be seen only by reflected light; i.e. the object must be illuminated to be seen. Further, the color of a non-luminous object depends in part upon the characteristics of the light source used to illuminate it.

INVESTIGATION:

Let us see what happens when a colored light strikes a colored surface. You will need:

- 6 color filters (red, blue, green, cyan, magenta and yellow).
- 7 sheets of colored construction paper (red, blue, green, yellow, cyan, magenta and black).
- a white light source.

Place a red filter in front of the white light source. One at a time, shine the transmitted red light onto each of the colored surfaces (construction paper). Record the color of each different surface when under the red light in a chart similar to Figure 20 (draw a chart on your paper). Repeat the preceding procedure for each different filter. It may be best to do this investigation in a darkened room.

COLOR OF LIGHT	COLOR OF SURFACE						
	RED	GREEN	BLUE	MAGENTA	CYAN	YELLOW	BLACK
RED							
GREEN							
BLUE							
MAGENTA							
CYAN							
YELLOW							

COLORED LIGHTS AND SURFACES
Fig. 20

Write out anwers to these questions:

Which colored surface stayed the same color?

Which colored surface appeared black or gray?

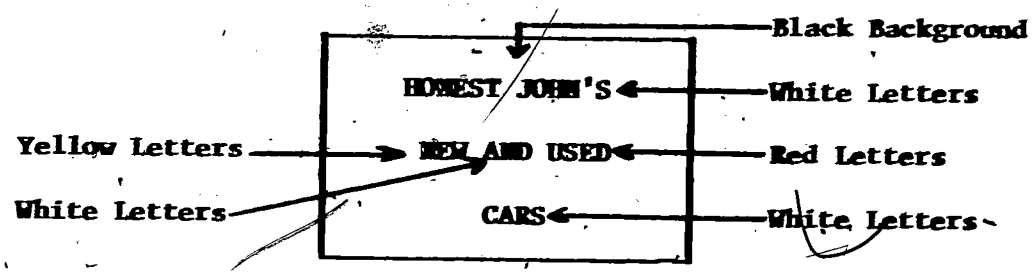
Which colored surface appeared to change color?

As you have seen, the color of the source of illumination has a great effect upon the color of a non-luminous material. In commerce and industry, types of lights can produce striking effects. Electric or gas lighting is usually deficient in violet and blue rays. Therefore, interior designers must note that blue substances will not reflect as much violet and blue light in such artificial light as they will in sunlight; such materials will appear darker and of a somewhat different "blueness" (tint) under artificial light as compared with their appearance in sunlight.

A striking effect of illumination upon the color of objects is provided by mercury vapor and sodium vapor street lights. The mercury vapor lamps give a bluish light which often leads to the mistaken impression that this lighting approximates daylight (you can see the mistake by referring to your chart from Resource Package 2-1); the sodium vapor lamps give a bright yellowish light that has a dramatic changing effect on an object's daylight color.

INVESTIGATION:

A sign painter tried to convince his customer that the following sign would not be a good idea for nighttime viewing under mercury vapor lighting:



The customer wanted the top and bottom lines in white with the word "NEW" in yellow and "USED" in red, with it all on a black background. Let's find out what the sign read under mercury vapor lighting at night.

You will need:

-- mercury vapor discharge tube

- sodium vapor discharge tube
- induction coil
- power supply
- support for the discharge tube
- Colored paper (blue, white, green yellow, black, orange, light red, brown and red)

Surround the mercury discharge tube with an enclosure so that only the light from the discharge tube will be able to strike the surface of the paper. Place the colored paper, one sheet at a time, inside the enclosure and record the observed color in a chart similar to Figure 21. After you have investigated all the colors, change the discharge tube and repeat the procedure.

Which color(s) stand out best under sodium vapor lighting? under mercury vapor lighting?

What would the car dealers sign read?

Color in Daylight	As Seen Under Sodium Vapor	As Seen Under Mercury Vapor
Blue		
White		
Green		
Yellow		
Black		
Orange		
Light Red		
Brown		
Red		

EFFECTS OF SODIUM AND MERCURY LIGHTS
Fig. 21

Make a study of some billboards or of an area that is lit with mercury vapor or sodium vapor lighting. For each sign, record the background color(s) and the color of the letters used, as seen by daylight.

After you have made your survey, compare the colors used with those that are best to use under sodium and mercury lighting.

RESOURCE PACKAGE 4-2.1

SELF-TEST

1) What is one of the whitest materials and about how much incident visible light does it absorb?

2) What is one of the blackest materials and how much incident visible light does it reflect?

3) Which color bands of the spectrum would be reflected by

   (a) a green car?

   (b) a white house?

   (c) a yellow flower?

4) What happens to the colors of white light when it passes through a combined red and green filter?

5) What happens to the colors in white light when it passes through a combined yellow and cyan filter?

6) Define hue, lightness, and saturation.

7) Should a meat market use lights rich in blues or reds? Explain your answer.

RESOURCE PACKAGE 4-2.2

ANSWERS TO SELF-TEST

1) Freshly-fallen snow; about 3-5%.

2) Black velvet; at least 3%.

3) (a) Mostly green with some red and blue.
   (b) All spectrum colors.
   (c) Mostly red, green and yellow bands.

4) You should see no color.

5) You should see green.

6) Hue - a dominant color in a material's spectrum.
   Lightness - the amount of light reflected from a surface.
   Saturation - the extent to which a certain wavelength (color) predominates over white light.

7) Red.

RESOURCE PACKAGE 5-1

COMPLEMENTARY COLORS

Complementary is a term used to express the relationship between two colors which, when combined, produce a complete spectrum of white light. Complementary colors for colored lights are not the same as for colored materials, because lights are from luminous sources and materials are non-luminous sources.

Two lights are complementary when, together, they form the spectrum of white light. For example, a red beam, consisting mostly of red and orange light, would be complementary to a greenish-blue beam composed of a mixture of yellow, blue, green and violet light; this is because the two colors, red and greenish-blue, combine to produce white light. Likewise, a magenta beam, made up of red, orange, blue and violet light, would be complementary to a green beam containing yellow and green light. In other words, if lights can add together to form white light, they are complementary.

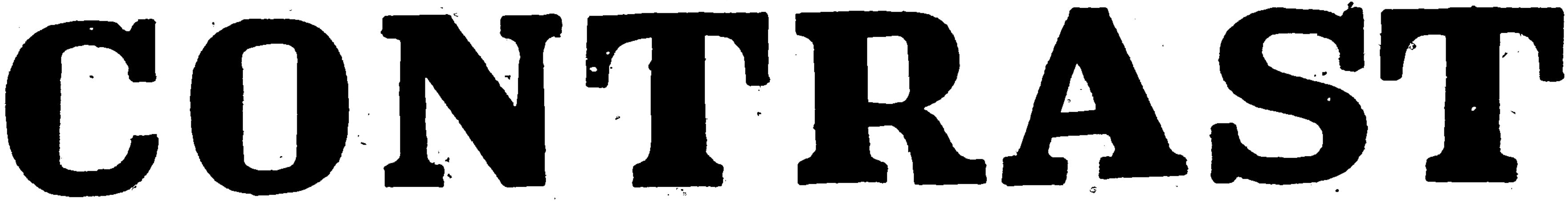
Two materials are complementary when, together, they produce black. In other words, one complementary material will absorb the light the other reflects. For example, yellow chalk, which transmits red, orange, yellow and green light and absorbs blue light, would be complementary to blue-violet chalk, which transmits blue and violet and absorbs green, yellow, orange and red light. If the two chalks are mixed or superimposed all of the components of white light will be absorbed, resulting in blackness. In other words, if colored pigments can together subtract out all the light that shines on them, they are complementary.

Because of the incomplete reflection and the incomplete absorption of pigmented materials, it is not easy to find two substances that are completely complementary to each other.

Since one complementary colored substance reflects those very spectral colors which the other does not, complementary substances usually furnish maximum contrast for each other; therefore, complementary colors are useful in providing contrast, such as yellow-green letters contrasting well against purple. What color would contrast well against blue? Of course, contrasts will be greatest when two complementary colors are of equal lightness. If one desires to make a color appear more intense, then the color used should be contrasted against a complementary color background which is darker then itself.

INVESTIGATION:

Place a sheet of translucent white paper (copy paper should do nicely) over the letters in Figure 22. On the copy paper, color the letters blue-green (cyan) and color the background red.. Try to keep the colors uniform in brightness; DO NOT outline the letters!



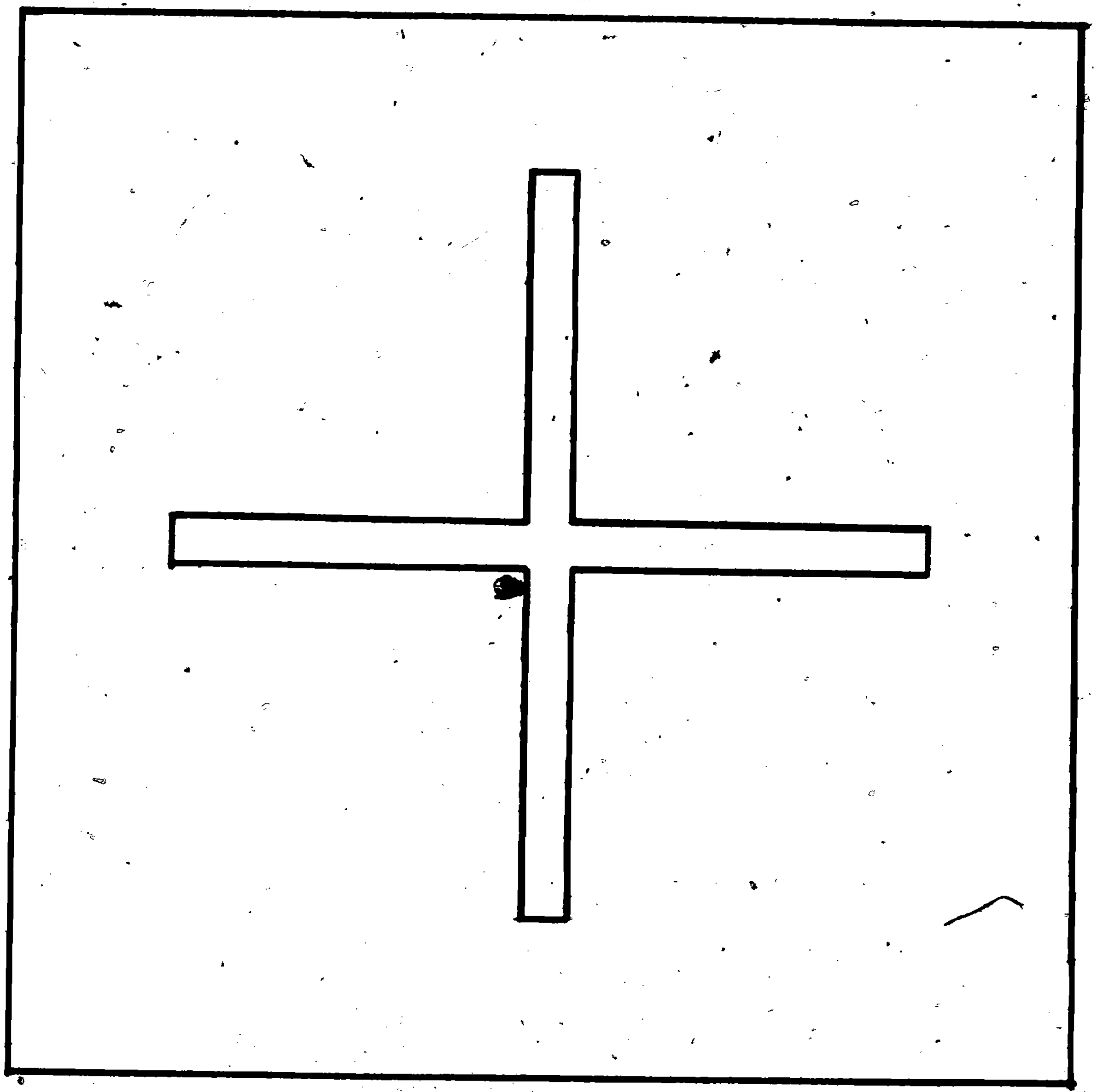
COMPLEMENTARY COLORS
Fig. 22

Examine the letters you have just colored. Due to the contrast of the complementary colors which you used, the edges of the letters may seem to vibrate. Here are some basic complementary colors (pigments):

Red - Cyan (blue-green)

Yellow - Blue

Green - Magenta (violet)



COMPLEMENTARY COLORS CROSS
Fig. 23

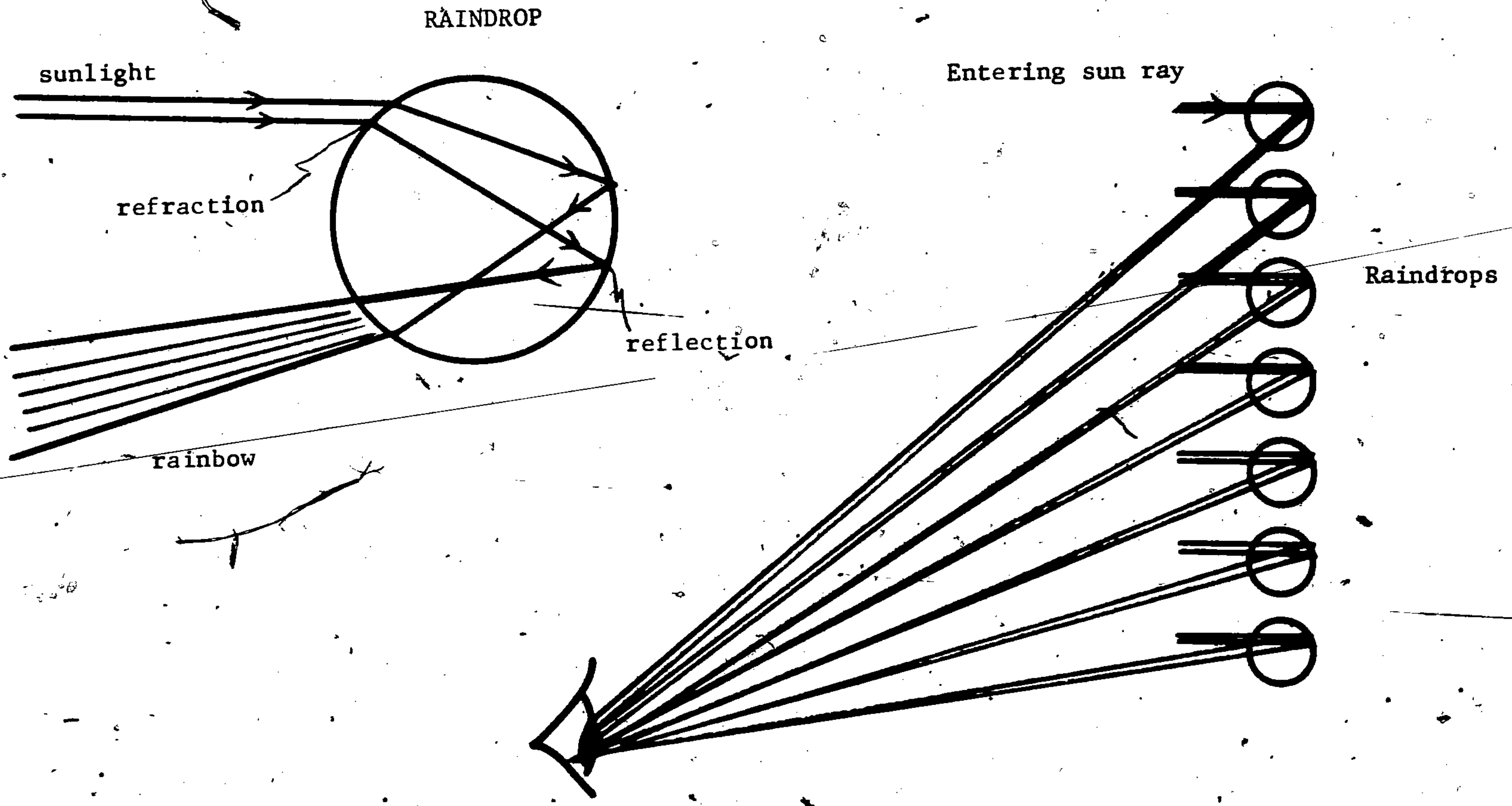
Trace a very light outline of Figure 23 on two different sheets of white paper. On the first, color the shaded area blue and the clear area yellow. On the second sheet, use magenta and green for these same areas.

Can you offer an explanation as to why there seems to be a vibration along the edges of the figures?

RESOURCE PACKAGE 6-1

RAINBOWS

The rainbow is produced by a combination of the refraction (bending) and the reflection (bouncing back) of light waves incident upon raindrops. Rainbows are seen from the ground only when the sun is behind the observer and is fairly low in the sky.



THE RAINBOW
Fig. 24

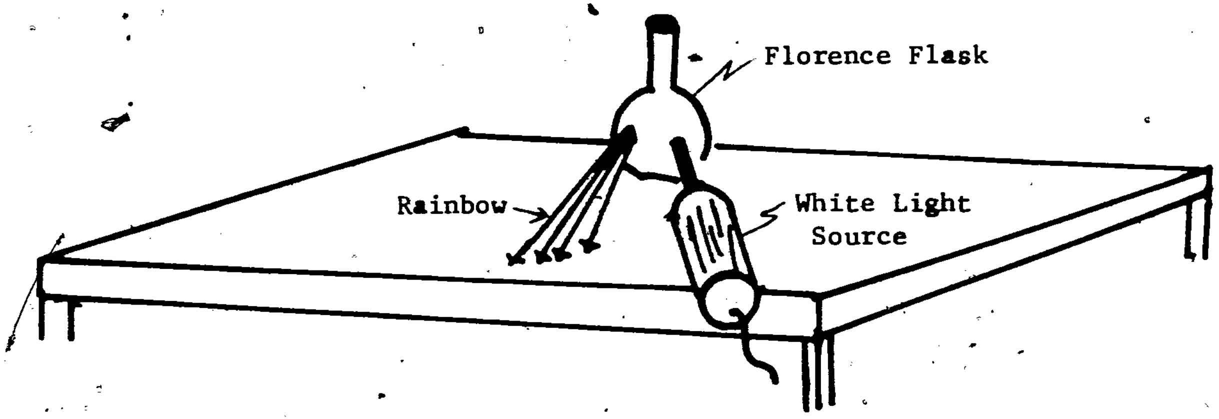
When a ray of sunlight enters a raindrop at a certain angle, it will be reflected by the back surface of the raindrop and emerge opposite the point of entry (see Figure 24). The two refractions occur as the light first enters and then as it leaves the raindrop; refraction produces a separation of the red, blue and other remaining six colors of the rainbow. Because the drops are far from the observer, a ray from a particular raindrop will reach the observer's eye; and a ray from a drop a distance of 3 feet or more away will produce the next colored ray which reaches the eye. Thus a droplet adds a particular color to the rainbow as seen by an observer at a particular location with respect to a droplet in the sky. Therefore, observers do not see the same rainbow at the same time and actually do not see the same arc.

INVESTIGATION:

To investigate the formation of a rainbow, you need:

-- 500 ml Florence (round) flask
-- light source
-- white paper
-- straight edge
-- protractor
-- white cardboard surface

Place the light and flask as shown in Figure 25 (on next page). First, the light rays should hit the flask near its center. Next, move the flask slowly and parallel to the light source. Once you have



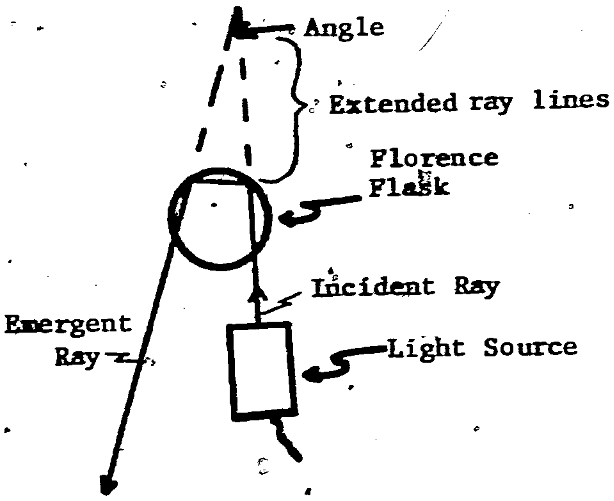
VIEWING A RAINBOW
Fig. 25

moved the flask to the proper location, you will see a spectrum similar to the one produced by a raindrop. Now, place a sheet of paper in front of the reflected beam and observe the colors. From your observation, what would be the order of colors found in a rainbow? Find a picture of a rainbow and compare your predictions.

A double rainbow is often seen in which a secondary bow is outside the first. This double bow is caused by double refraction; the secondary bow is not as bright as the first, and the colors are in <u>opposite</u> order.

Why does a rainbow arc? (You should have been able to see a slight arc in the rainbow produced by the Florence flask!) It can be shown that the angle between the sunlight's entering a droplet and emerging is about 42^{o} for the principal rainbow and 52^{o} for the secondary rainbow. All of the droplets in the sky which make an angle of 42° between the ground observer and the sun will produce a vertical circle of colored rays. This circle is normally cut off by the ground; however, completely circular rainbows can be seen from high cliffs, mountains or airplanes.

Now, with the same Florence flask set-up, but with a larger sheet of paper under the flask, line a straight edge up with the incident ray and mark this line on the paper (see Figure 26). Repeat the same procedure for the emergert ray. After you have marked the path of both rays, remove the flask and extend the ray lines until they intersect. Use a protractor to measure the angle between the two lines. How does the angle you measured compare to that produced by a rainbow's raindrop? Discuss this answer.



MEASURING BENDING ANGLES
Fig. 26

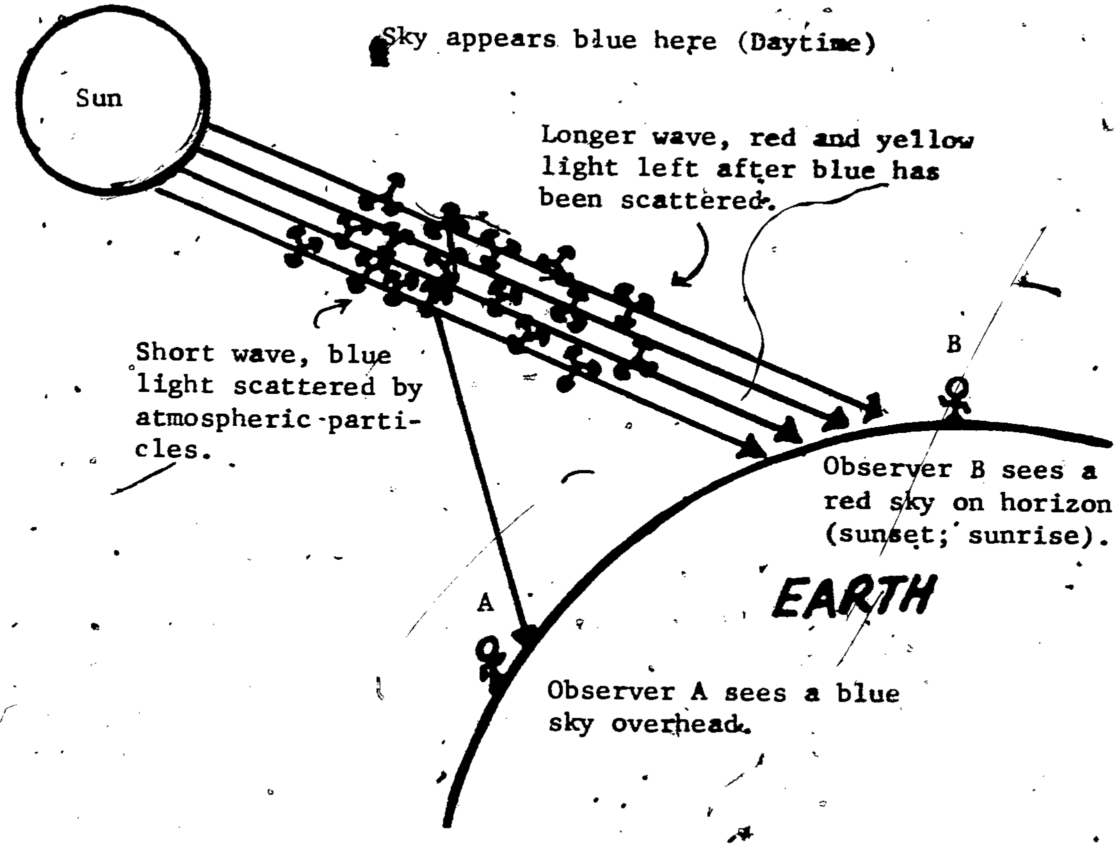
Now that you have studied the rainbow and how it is produced, consider the following question: Is there ever a time when the sun is shining and when droplets are present that the sun will not produce a rainbow?

RESOURCE PACKAGE J-1

BLUE SKIES

Is the earth's sky the same color as the moon's sky? The answer is "No." The reason the earth's sky is colored is because the sun's rays are scattered by minute particles of dust, water droplets, atmospheric pollutants and air molecules. On the moon, there is no air, vapor, pollutants or dust in the atmosphere, so the moon dweller would see a black sky with the sun appearing as a sharp-edged circular disc of blinding light.

It turns out that long light waves can move past comparatively small obstacles and be relatively undisturbed; whereas shorter waves are more likely to be affected by the same obstacles. Applying this thought to the wavelengths of the colors in the spectrum and remembering that blue has the shortest wavelength and red the longest, it could be expected that tiny particles in the atmosphere would scatter blue light more than red. So, as sunlight passes through the atmosphere, the blue rays are scattered toward the earth and give the sky a blue appearance (see Figure 27).



BLUE SKY AND RED SUNSET OR SUNRISE
Fig. 27

For an observer of a sunrise or a sunset, sunlight has to travel through a thicker portion of atmosphere than for an observer at other times during the day. Because of this increased atmospheric thickness, the shorter rays (blue) are scattered more; and, therefore, a larger percentage of those rays which reach the observer are those longer wavelength yellow-orange, or nearly-red, rays (see Fig. 27, above).

As an exercise, watch the sunrise or sunset and record the different colors that appear. Any crimson and purple colors present will be due to absorption of certain colors by thin clouds.

As a practical application, consider that certain colored automobile headlights are better for foggy conditions than are other colors. What colors would you recommend for fog lamps on automobiles and trucks? Why?

RESOURCE PACKAGE 8-1

COLORS IN THIN FILMS

It is common to see bright colors in thin films of soap bubbles or in thin films of oil on water. Surprisingly, these brilliant colors will appear even when the soap, the water, and the oil are themselves not colored materials.

INVESTIGATION:

Take two microscope slides and press them together between your thumb and forefinger (It may be necessary to use both hands). Slowly rotate the hand(s) until you see colors between the two slides. The colors you see are produced because of a thin layer of air between the slides and the reflection of light off two different film surfaces. Where the air film thickness is about the same distance as the wavelength of light, colors are produced by interference between the light rays which are reflected from the lower surface of the top slide and those which are reflected from the top surface of the bottom slide. Light rays of just the right wavelength will reinforce (add to) each other as they are reflected and will appear as a given color; whereas, rays of any other wavelength will be thrown out of step with each other and will cancel one another out. This cancellation permits only certain colors to appear.

The thin film phenomenon was first recorded by Isaac Newton over 300 years ago. A parctical use of the phenomenon of thin film interference (color production) is to checks materials for smoothness. For example, you can tell how smooth your microscope slide surfaces are by observing the regularity of the color patterns formed. The smoother the surfaces, the more regular (uniform) are the patterns.

The colors of thin films of oil and soap are produced in the same manner as the colors produced between the microscope slides. If a particular place on a soap film is the right thickness, colors of a certain wavelength will be removed, while the other wavelengths (colors) of the white light spectrum will appear. Thus, the reflected light would contain all wavelengths except the one removed. If the violet wavelength were the one removed by a soap film at a particular region, then the region would appear greenish-yellow. In another location, the bubble surface might appear bluish-red, indicating that the wavelengths of green have been removed. Since soap bubbles vary in thickness, every color wavelength will have some location where it is cancelled by interference; and so every possible complementary color appears somewhere on the bubble.

INVESTIGATION OF OIL FILMS:

To study the colors produced by interference, you need the following:

flat shallow pan (black or with black paper in the bottom) with 1 or 2 cm of water

light source

various kinds of oil (turpentine; "3-in-1" oil; SAE 20 motor oil; olive oil; corn oil; safflower oil; etc.)

Start with clean water. Place the light source so that it reflects off the center of the pan. In the center of the reflected light place one drop of oil. Observe the color patterns as the drop spreads out.

After the pattern settles down, write a simple description of what you see. Add another drop of oil and record what you see. Discard the water; clean the pan well; and repeat the previous procedure for each of the various kinds of oil. Notice that turpentine gives rapid color changes. Can you explain why?

INVESTIGATION OF SOAP FILMS:

To investigate the colors in soap films, you need a soap solution and a wire hoop about 8 cm (3 in) in diameter and attached to a handle. A good soap solution can be made with the following ingredients:

-- 150 ml distilled water

-- 150 ml glycerin

-- 150 ml liquid Woolite

This solution will produce poor bubbles, but it will produce a long-lasting film. Glycerin is added to stabilize the film. Less glycerin will produce a thinner, but less stable film. If you have trouble with breakage of the film, add more glycerin. The wire ring needs to be as circular and as flat as possible. You will also need:

-- shallow bowl

-- light source

-- prism

-- piece of white cardboard

Arrange the light source and prism so that a white light spectrum falls on the piece of white cardboard. Dip the ring in the bubble solution until there is a film of soap solution on the ring. Use the film on the ring like a mirror and observe the reflection of the white light spectrum in the soap film. Next, the ring should be mounted. It is an interesting trick to wait for awhile after mounting the ring, observing the changes in the film. Observe and record the differences between what you see on the screen and what you see in the reflection in the film.

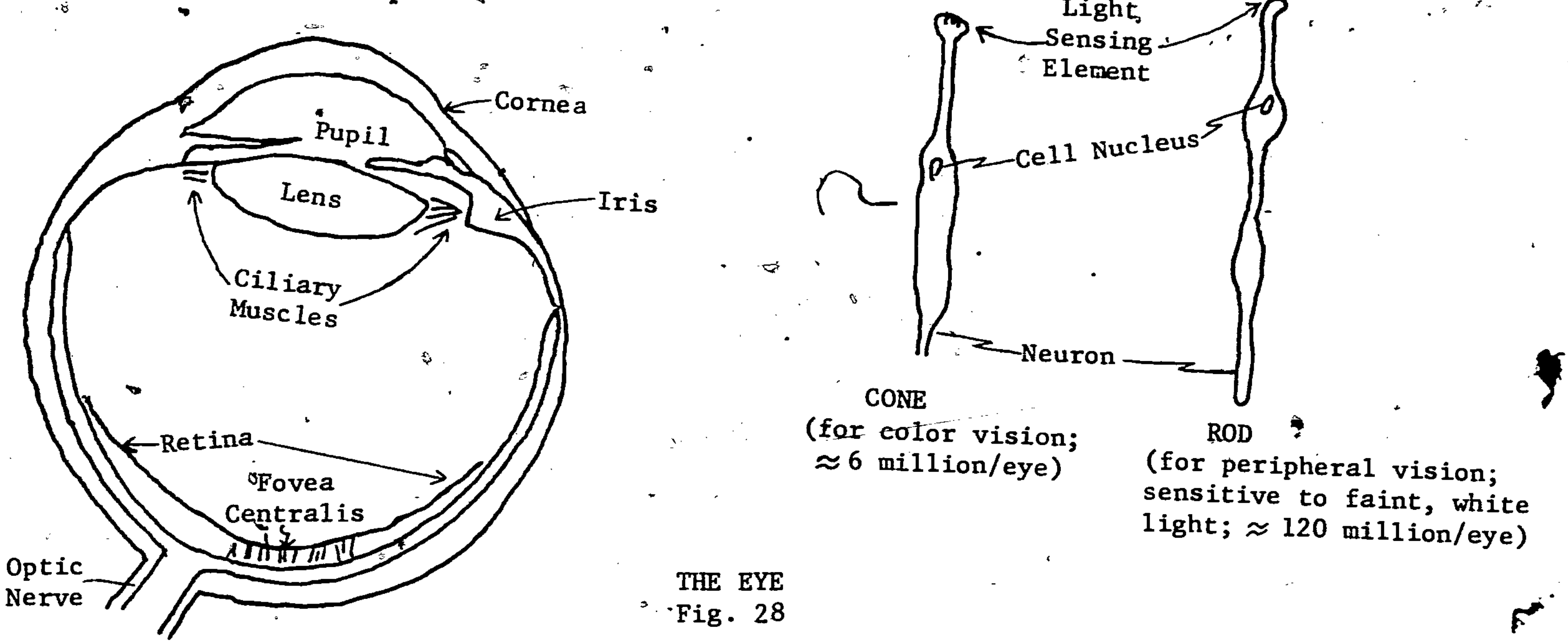
What is unusual about the reflection of the spectrum in your film? Continue to observe the reflection for some period of time. Record any changes you see.

Nature provides several cases of colors produced by interference. The colors of Mother-of-pearl are produced by interference from very thin layers of calcium carbonate (marble) on the inside of the oyster shell. The brilliant colors of a peacock's tail, a dragon-fly's wings or a beetle's wings are further examples of the interference effect. No colored materials are present in any of these examples; each simply breaks up white light by interference and produces vivid colors.

RESOURCE PACKAGE 9-1

COLOR VISION

The part of the eye directly concerned with color vision is the retina (See Figure 28). The retina is the thin transparent lining of nerve tissue on the inner wall of the eyeball, where incident light energy is turned into electrical impulses by the nerves. These electrical impulses travel via the optic nerve to the brain, where the sensation of sight is produced. The retina is composed of a complex arrangement of nerve cells and nerve fibers containing millions of thin rod and conical-shaped light sensors (the rods and the cones). Rods and cones are located along the back side of the retina (the side toward the brain); therefore, light must travel through the outer nerve layers to reach these sensors.



THE EYE
Fig. 28

It is believed that the first vision reaction within the retina is for the rods and cones to decompose a substance within them of a photo-chemical nature. The decomposition product then produces a nerve impulse which is transmitted to the brain. This photo-chemical material is a purple-colored substance located in the rods and cones, and is known as visual purple or phodopsin. Because the light-sensitive.photo-chemical is decomposed during "seeing", it must be continuously reformed within the rods and cones(even as they are broken down) in order to maintain the eye's sensitivity.

The most sensitive region of the retina, giving the best visual acuity (fine detail), is the fovea centralis. The highest concentration of cones is located in this area (no fewer than 100,000). As one travels away from the central region, the proportion of rods to cones changes until at the edge of the retina only rods are present. It is estimated that there are over 100 million rods and perhaps 6 million cones in the retina. The rods are light detectors for low-intensity vision. Rods are sensitive to faint light but do not give a distinct or sharp image, nor do they perceive color. The cones operate only in light of moderate or high intensity, and are the organs of precise sight and of color vision.

The exact method by which the color-sensitive cones distinguish one color from another is not completely understood, and has been the subject of much investigation. Thomas Young, in the early nineteenth century, proposed a currently popular three-color theory of vision. And recent research which substantiates (backs up) the three-color theory, lies in evidence that the cones possess three photosensitive substances--one which absorbs mainly red wavelengths, another mainly green wavelengths, and a third mainly blue wavelengths. The sensation of seeing colors other than red, blue, and green arises from a combination of different degrees of reception of red, blue and green light by the three recrptor substances.

In order to distinguish color, the cones of the retina must react according to the wavelength(s) of the incoming light. While the three--color theory assumes that the cones are essentially of three light-sensitive kinds, it also assumes that they are each senitive to a wide band in the spectrum but most sensitive in the three respective different regions of red, green and blue. When light strikes the retina, each kind of cone reacts according to its sensitivity to the composition of the light, and combinations of the three responses produce the wide arrary of color sensations perceived by the brain. For example, because the sensation of yellow can be obtained from a mixture of pure red light with pure green light (each containing no true yellow light), it can be inferred (assumed) that the eye contains no actual yellow-sensitive conse; further, because a beam of pure yellow light (containing no red or green light) is seen as yellow, it can be inferred that pure yellow stimulates both the red- and green-sensitive cones to produce a yellow sensation (with no response from the blue-sensitive cones). The sensitivity of each cone to light over a broad region of the spectrum is inferred (indicated) from the fact that wavelengths of three colored rays can vary considerably and still produce the sensation of white light.

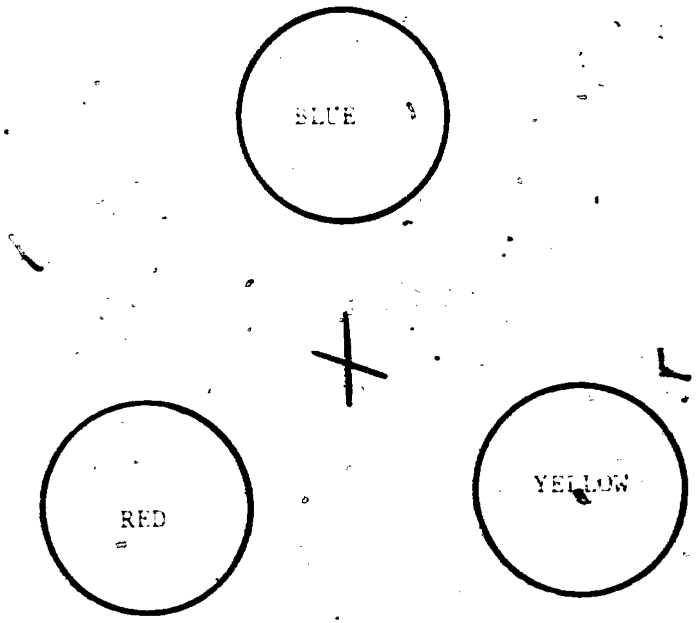
Since the eye is sensitive to the range of wavelengths between approximately 400nm and 700nm, it is not surprising that the eye is not equally sensitive to all wavelengths within these limits. Comparing light waves of equal energy, the eye is most sensitive to rays in the middle of the spectrum with a wavelength of about 550nm--yellow-green rays. Eye sensitivity decreases very rapidly toward the red and toward the blue bands. Thus, for the normal eye, green and yellow rays are more effective for a given energy than a blue or red ray. It is for this reason that policepersons' raincoats, life rafts and some fire trucks are being painted a yellow-green color.

The variation of visual sensitivity with wavelengths for the average eye was illustrated in Figure 3 of Resource Package 1-1. In addition to the intensity changes of Figure 3, eye sensitivity changes as the intensity of illumination diminishes. Specifically, as illumination decreases, the maximum sensitivity changes from the 550nm of Figure 3, to 510nm. This change occurs because the rods, although not color selective, are most sensitive to bluish-green light. This sensitivity shift is known as the Purkinje Effect. Under dim illumination the eye's sensitivity to blue and to green light is much greater than it is at normal levels of illumination, as compared to its sensitivity to red light; a feature related to this Purkinje Effect is the darkening of red and orange reflective surfaces under blue-green light. The Purkinje Effect can also be used to explain why the moon is often painted as bluish-purple, while, in fact, its spectral distribution is similar to that of the sun(Its light is, of course, simply reflected sunlight).

The sensitivity of the eye is remarkable in its ability to adapt to changing conditions of illumination intensity, but the eye does not have the same sensitivity to changes in color. If the eye gazes at one distinct colored material for more than a few seconds, it seems to become fatigued to the color of light received from the object. Thus, if a color-fatigued eye looks at a white surface, the surface will appear to be a color complementary to that of the colored object.

INVESTIGATION OF COLOR FATIGUE:

Place a plain white sheet of paper over the circles in Figure 29 (on the next page) and color in (color trace) each circle, using the color indicated within that circle. Also, place an X on your paper in same location as indicated in the figure. Make the circles dark and uniform in color, but do not outline them. Now, gaze steadily at the cross between the colored discs for about two minutes, and then look quickly at a plain white sheet of paper or white wall. You should see the respective complementary color for each disc. Do the complementary colors you see seem lighter? Explain (Consider the white surface and ~~the~~ ideas of tint and reflectivity). What color did you see for each respective disc?

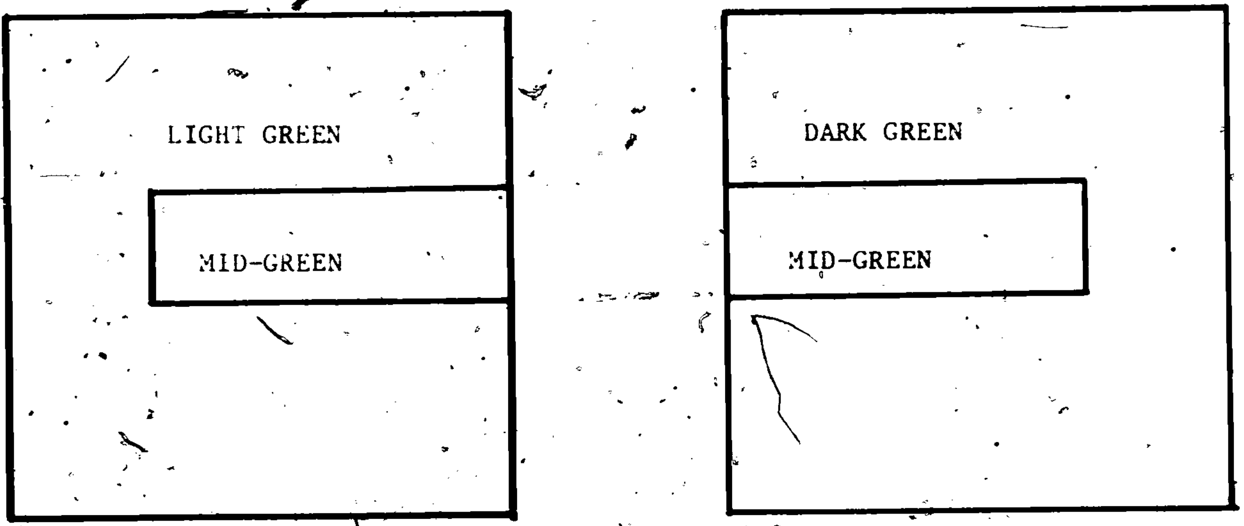


COLOR FATIGUE
Fig. 29

The ability of the eye to change according to illumination intensity and according to color, produces important effects when different tones or shades of gray or of colors are placed side by side (juxtaposed). The visual impression when two different grays are placed alongside each other is that their contrast increases; a similar optical impression of contrast is obtained when the same shades of color are viewed against different tones of that color.

INVESTIGATING JUXTAPOSITION OF COLOR:

Select three different shades of green crayons or pencil colors, say a mid-green, a light green and a dark green; then color Figure 30 as lettered below. (Do this on a separate sheet of white paper, not in the minicourse, please.)

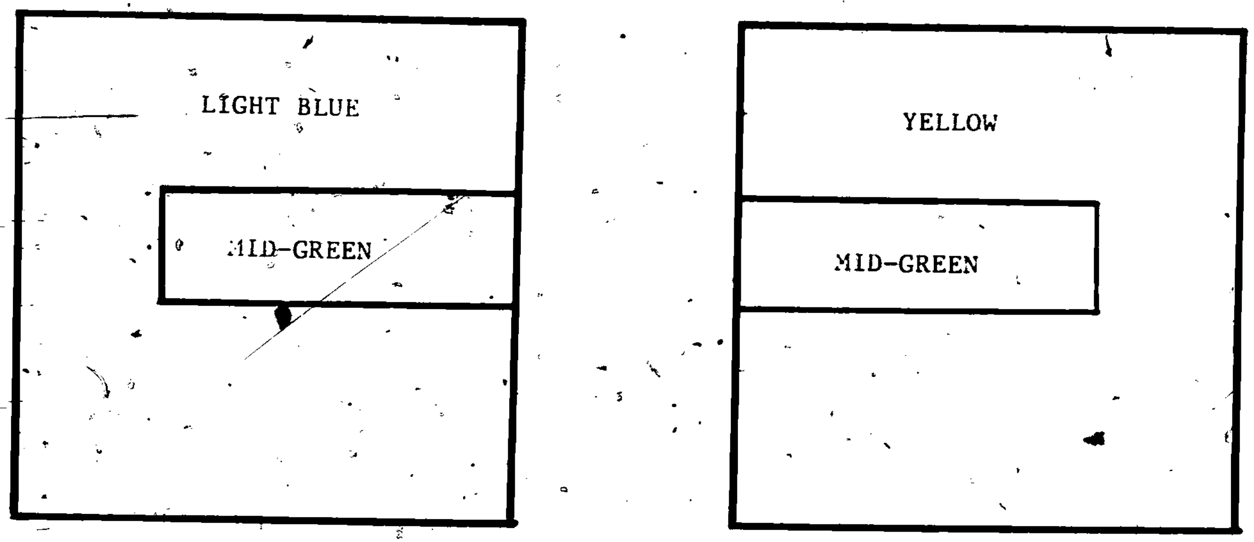


COLOR JUXTAPOSITION
Fig. 30

This type of contrast is known as simultaneous tone, lightness, brightness, or contrast and these effects explain partially why photographic prints made from color transparencies are sometimes a disappointment. The transparencies are usually projected and viewed in a dark room so that the surroundings are dark; but the prints made from these transparencies usually appear lighter in comparison because they tend to be darkened by their light border.

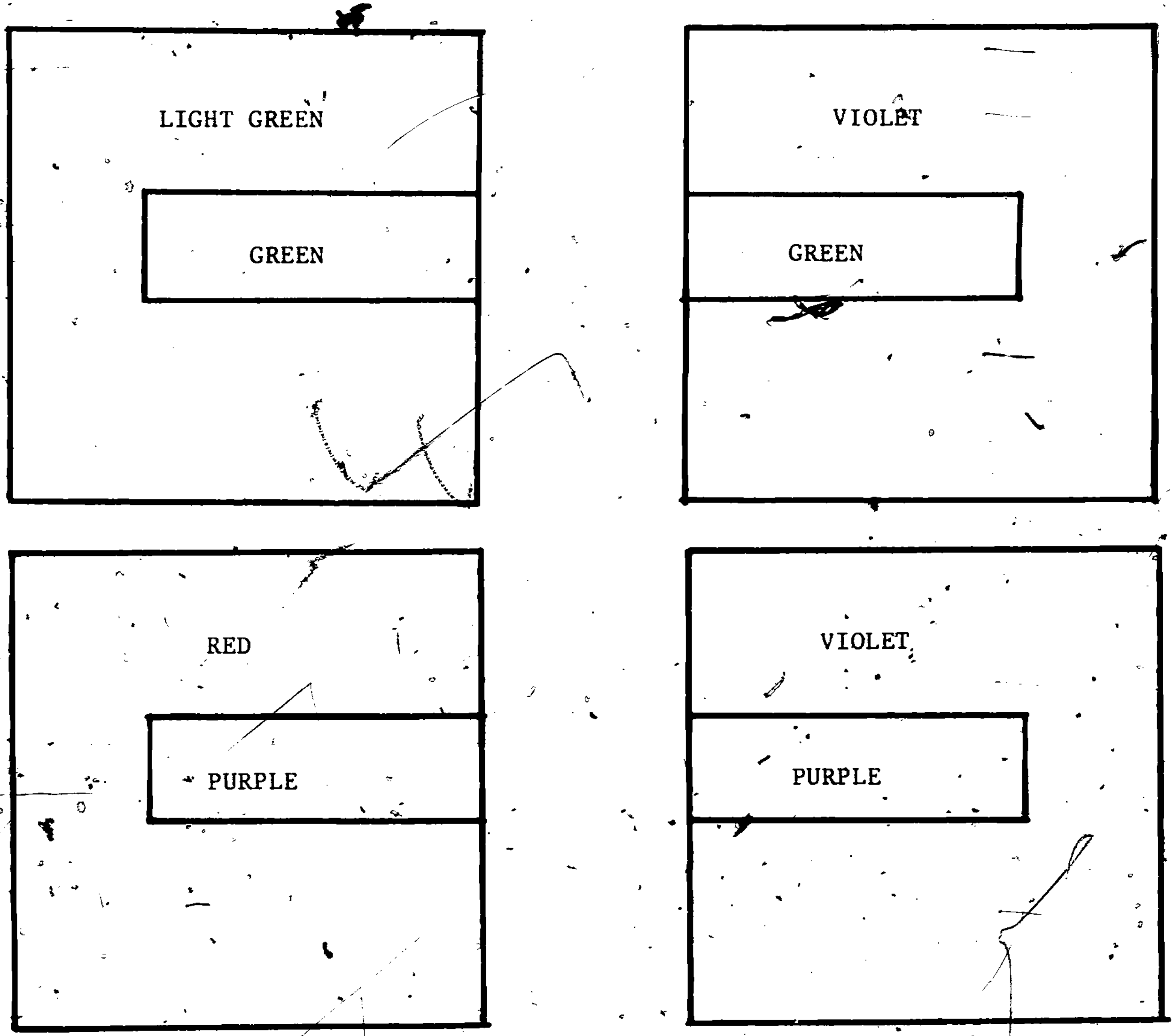
When different colors are placed together, side by side, a small change in the appearance of the colors usually occurs. This change in appearance is known as simultaneous contrast of color or hue. A yellow flower is usually deepened by contrast with surrounding green leaves. Green foliage of a tree will appear to change in hue if seen first against a blue sky and next against brown earth.

Color Figure 31 as indicated. You should notice a difference in the apparent color of the mid-green. In the left hand case, the green tends toward yellowish-green; and in the right hand, toward a bluish-green.

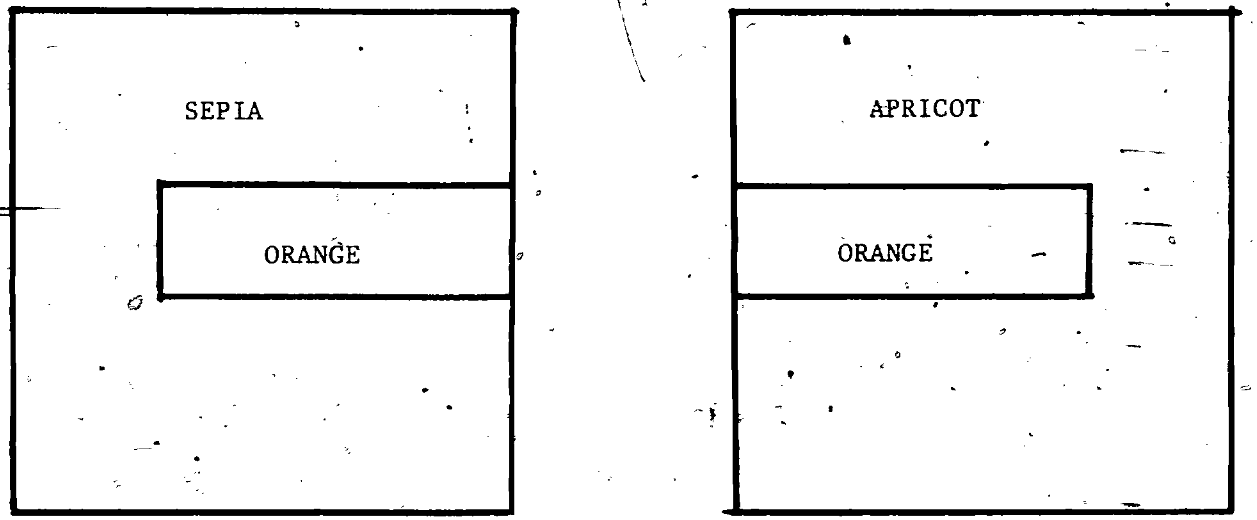


MORE COLOR JUXTAPOSITION,
Fig. 31

Now place a gray patch of something against a bright red background. The gray patch should appear bluish-green. For other examples of color contrast, color Figures 32 and 33 as indicated.



COLOR JUXTAPOSITION
Fig. 32



COLOR JUXTAPOSITION
Fig. 33

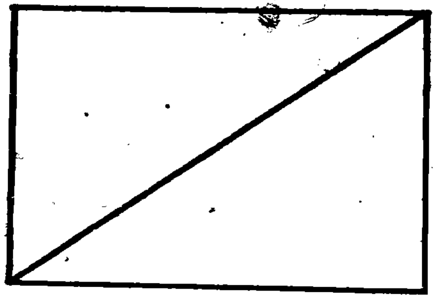
Lightly tinted colors like pale cream or magnolia appear white when viewed alone (that is, without comparison to another color); but when laid against a pure white surface, they are seen to be definitely colored. This indicates that our perception of color is a relative thing, and it hints at the importance of the mind in interpreting the optical signals the eye actually receives.

Artists frequently refer to red, orange, yellow, and yellow-green as warm colors, and to blue, bluish-green, and purple as cold colors. Because yellow is highly reflective, it is frequently referred to as a bright color.

It is usually artistically desirable that various colors should appear to agree pleasantly when seen together; that is, the colors should harmonize with one another. As a general rule, harmony will be obtained when light of at least one color is present in the spectrum of both materials under consideration, just as contrast or discord is generally produced when there is no color common to the reflected or transmitted rays from two materials. For example, an orange-red tends to contrast or clash with a mid-blue; whereas a magenta or purplish-red will harmonize with the blue; vice versa. a purple-blue will blend with the orange-red. Other harmonious combinations, termed analogous colors by designers, are orange with yellow, red or blue with purple, green with either yellow or blue, and red or brown with orange or yellow. Shades or tints of the same hue, termed self-colored harmonies, are extensively used by artists and designers in paintings, fabrics, carpets, wallpapers, ceramics, etc. with pleasant effects.

INVESTIGATING CONTRASTS AND HARMONIES:

Draw four rectangles, as shown in Figure 34, on a sheet of white paper. Pick four pairs of contrasting colors from a box of crayons o[illegible]ored pencils (A box of 64 crayons is a good source). Next, color the four rectangles, using one pair of contrasting colors for each rectangle. (Use one color for one side; the other color for the other side of the rectangle.)



CONTRASTS AND HARMONIES
Fig. 34

After you have worked with the contrasting colors, draw six of the same figures on another sheet of white paper. Now select six pairs of harmonious colors, and color the figures as you did for the contrasting colors.

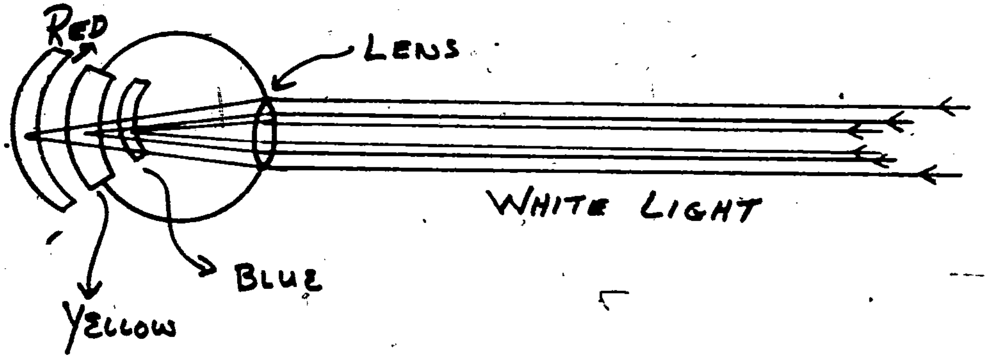
The effects of contrast between hues and between colors is sometimes called the <u>Law of Juxtaposition</u>. This Law <u>states</u> that when different colors or tones (hues) are seen together, they appear as dissimilar as possible. This phenomenon is connected with the color fatigue which results from the continual movement of the eyes from one color (hue) to the other. Color fatigue is noticed most when a small area of color is seen against a large area of another color.

The apparent <u>size</u> of the smaller colored area is also effected; colored lettering tends to look larger on a different colored background than it does on a white background.

The Law of Juxtaposition of color can be used to advantage by the specialist in color, but the contrast effect between tones is not always a valid assumption. Whenever two components are small in area and are seen together as narrow-striped patterns or as fairly fine mosaics, the opposite effect to the Juxtaposition Law may occur. Under these circumstances, the colors will seem to become more like each other. In tweed textiles, for example, different threads before weaving may be brilliant and contrasting in color, yet when seen in the fabric, these threads appear much less brilliant. In fact, in many cases, thread colors combine to yield the effect of a third color.

THE EYE

A lens of the type found in the eye, double convex, may be considered approximately similar to two triangular prisms placed base to base. Thus, just as a prism separates white light into its components, so does the lens of the eye. This means that the lens in the eye does not bring rays of different wavelengths to the same location (focus point) on the retina. The greatest separation of focal points is between the focal point of the short, violet waves and the focal point of the long, red waves. The name of this separation of the focal points of various colors within a beam of light is chromatic aberration. Because the spreading (diffracting) of violet and blue light is greater than that of red light, violet and blue rays are brought to a focus slightly in front of the retina; red rays are focused slightly behind the retina (see Figure 35).



CHROMATIC ABERRATION
Fig. 35

Chromatic aberration of the eye is not usually noticed in daily life because the sensitivity of the eye is greatest to yellow-green light near the middle of the spectrum (sensitivity decreases on either side of this yellow-green maximum). The violet and red rays do not focus precisely at the yellow-green position, but the brain senses that a greenish image is focused on the retina, with violet and red fringes; the overall effect interpreted by the brain is that it is seeing a white, focused image.

Under certain conditions, chromatic aberration of the eye may be troublesome. For example, it can cause unpleasant fatigue when reading bright red letters against a blue background; and in a room illuminated only by blue or violet light, a person with normal vision may become short-sighted.

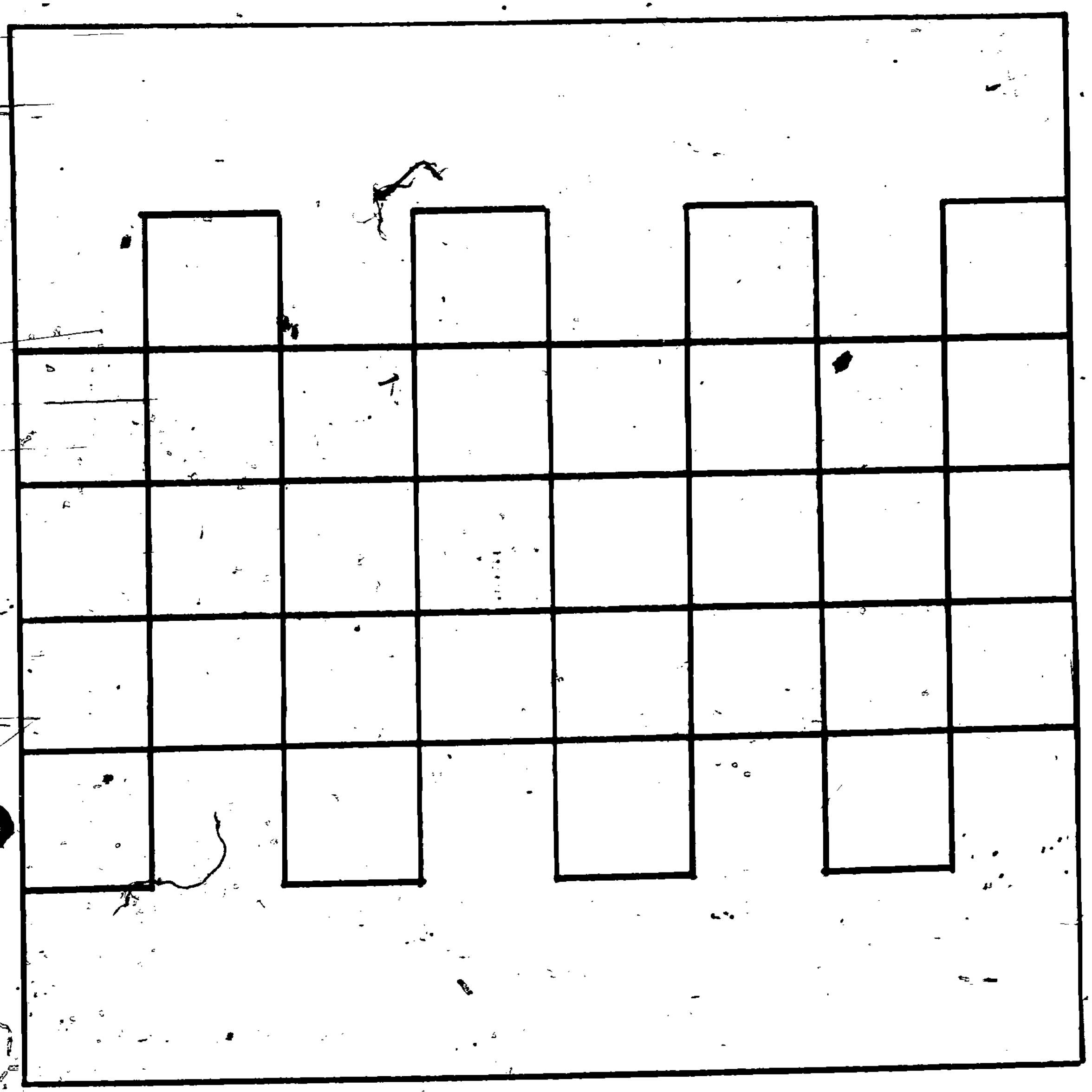
Since the eye will focus only on one object or point at a time, and since the colors of objects in juxtaposition affect vision, color and spatial (geometrical) combinations can be used to confuse the eye.

INVESTIGATING VIBRATING FIGURES:

Make an outline of the drawings shown in Figures 36 and 37 on pages 100 and 101. Color the shaded area red ~~and the other~~ area green. These should provide you with good examples of vibrating figures.

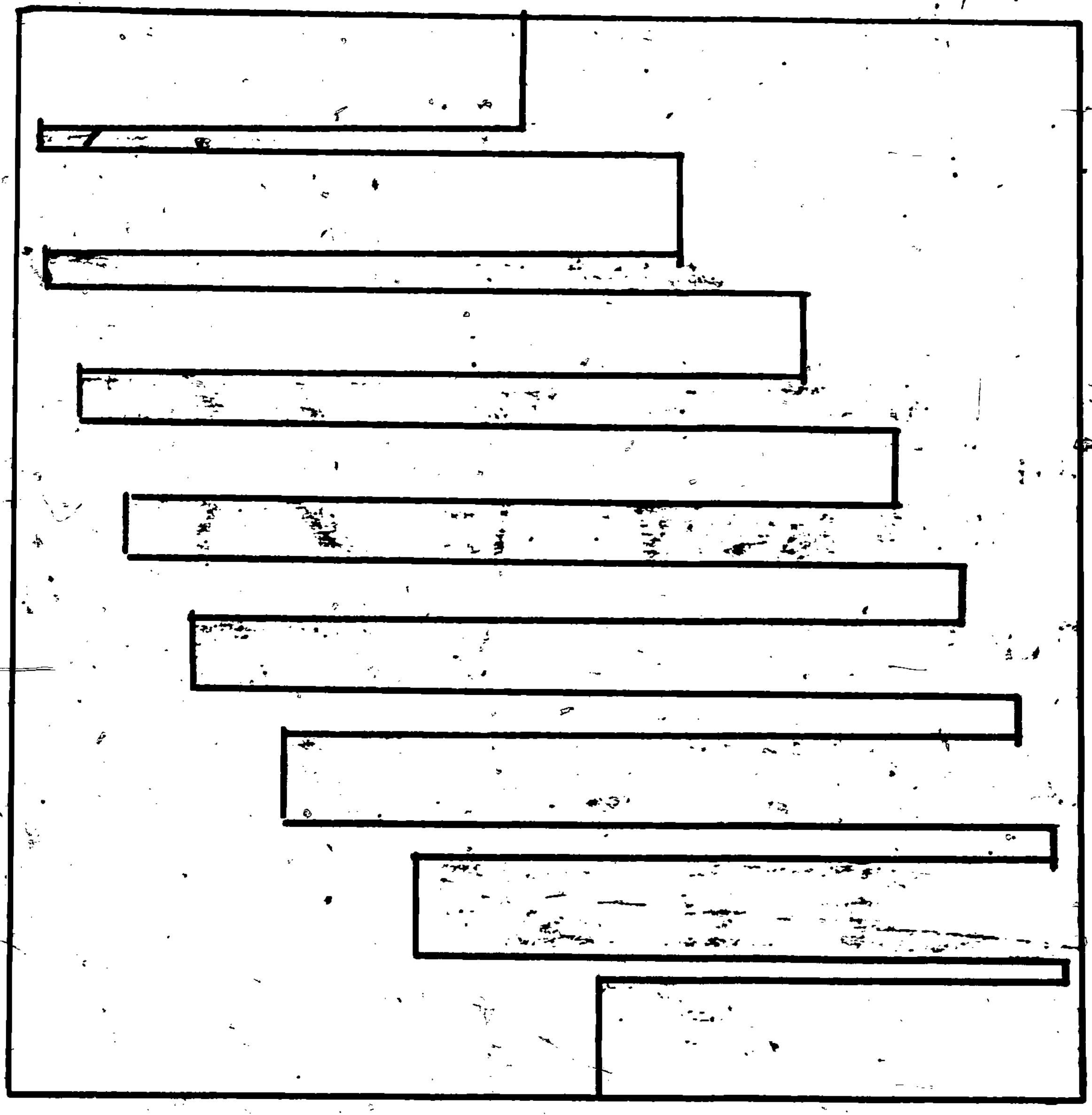
Write out explanations (answers) for the following:

1. At dusk, we see objects as light, dark, and shades of gray.
2. Scientists tell us that stars are of many colors, such as red, yellow, blue, white, green, etc. Why do people believe that the stars are white?
3. Why do night navigators aboard aircraft, ships, submarines, etc. work in chart rooms which are illuminated in red?
4. ~~Why might~~ a person with normal vision seem short-sighted in a room illuminated by blue light, but seem far-sighted inside a red-lighted room?



VIBRATING FIGURES

Fig. 36



VIBRATING FIGURES
Fig. 37

RESOURCE PACKAGE 10-1

ADDITIVE COLOR MIXING

We are now ready to consider how colored lights (luminous sources) can be mixed or blended to produce various other colors. This method is known as <u>additive mixing</u>.

You can produce a rainbow spectrum by passing a beam of sunlight through a glass prism. You can also do the opposite and combine (add) colored rays of the rainbow to form white light. The latter is accomplished by passing the rainbow spectrum through a second prism which recombines the colored lights into white, a reversal of the fromer phenomenon. Such combining and <u>dispersing</u> (spreading out) of colors demonstrates that white light can be produced by mixing or adding together the colored component lights of the white light spectrum.

Using initial letters to represent the six principal colored bands in the solar spectrum, we can represent this spectrum as the following sum (addition) of colors:

$$W = R + O + Y + G + B + V.$$

Now, recall from your previous readings about the nature of color vision, that the sensation of whiteness can be obtained by combining only three light rays (red, yellow ~~and green); or:~~

$$W = R + G + B.$$

Also, since a pure yellow light is theorized to stimulate both the red- and green-sensitive cones in the retina, white light sensation can also be obtained by:

$$W = Y + B.$$

Whiteness can also be obtained with mixtures of two complementary colored lights. Greenish-blue (cyan) mixed with red gives whiteness; and so does a mixture of selected purple and green lights. Like the mixtures of yellow and blue lights, all of the above ways to obtain whiteness are in agreement with the theory of three-color vision. And from the theory of three-color vision comes the "red, green and blue triad."

Besides combining to yield the sensation of whiteness, appropriate variations between triad intensities and proportions yield a wide range of color sensations. For this reason, lights of these colors provide the basis of nearly all additive methods of color reproduction and are referred to as the light primary colors or the additive primaries. Using the previous notation for white: $W = R + G + B$, can you see that green-blue (cyan) can be produced by white light minus red light ($W - R = G + B$)? Likewise, magenta is $W - G = R + B$ (white light minus green). Yellow light, you may recall, was derivable from $R + G$; therefore, $W - B = R + G$ (which is yellow). So yellow can be described as white light minus blue!

The description of white light minus red, green or blue is useful in many cases where mixtures of light result from reflection or transmission by colored materials. Yellow materials particularly reflect large proportions of red, orange, yellow and green light; that is, white light minus blue. Since magenta is not a special color, but green is, magenta is referred to as minus green. Can you come up with a name for yellow and cyan, using this same approach?

If a beam of white light is projected through a piece of blue glass (which absorbs red, orange and yellow), the apparently blue beam leaving the glass will contain green, blue and violet and may be represented by $G + B + V$. If a second white beam is projected through yellow glass (which absorbs only blue and violet light), the yellow beam leaving the glass will look yellow but will contain red, orange, yellow and green and may be represented by $R + O + Y + G$. If these two transmitted beams (apparently blue and apparently yellow) are projected simultaneously onto a screen, the resulting mixture on the screen is the addition:

$$\begin{array}{lll} & \text{Yellow Beam} & = R + O + Y + G \\ & \quad + & \\ & \underline{\text{Blue Beam}} & = \underline{\ G + B + V} \\ & \quad \text{Mixture} & = \underline{R + O + Y + 2G + B + V} \\ \text{Color:} & \text{Pale Green} & = (R + O + Y + G + B + V) + G \end{array}$$

Can you see that this mixture contains all of the ingredients of white light, but has an excess of green light and will appear to be a bright, pale green to the eye?

The same mathematical results can be the use of the chromatic (color) triad: $W = R + G + B$

$$\begin{array}{ll} \text{Cyan Beam} & = \quad G + B \\ \quad + & \\ \underline{\text{Yellow Beam}} & \underline{= R + G} \\ \text{Mixture} & = R + 2G + B \end{array}$$

R + 2G + B is white plus green, also yielding a pale green.

Assume there are three projection lanterns. In front of the first one a red-orange filter is placed so that it looks red; in front of the second, a yellow-green filter is placed so it looks green; and in front of the third, a blue-violet filter is placed so that it appears to be blue. In other words, each of the projectors separately would supply an apparently red, green and blue beam of light; each beam would comprise one-third of the spectrum and the results obtained by the merging of these beams can be predicted using the following notation:

(a) Red Beam = R + O
\+
Green Beam = Y + G

Mixture = R + O + Y + G
(yellow)

(b) Red Beam = R + O
\+
Blue Beam = B + V

Mixture = R + O + B + V
(magenta)

(c) Green Beam = Y + G
\+
Blue Beam = B + V

Mixture = Y + G + B + V
(cyan)

(d) Red Beam = R + O
+
Green Beam = Y + G
+
Blue Beam = B + V

Mixture = R + O + Y + G + B + V
(white)

Thus, six colors and white are obtained; and since these results are produced by adding beams of light to one another, the colors are really bright and ~~vivid~~. If the intensity of the light from each projector is controlled and varied, the range of colors can be greatly increased and a wide variety of tones of all the colors can be obtained.

INVESTIGATING ADDITION OF LIGHTS:

You will need:

-- 6 color filters (red, green, blue, yellow, cyan and magenta)
-- 3 source lights
-- white background (screen)

To find out what happens when colored lights are mixed, first predict the color you will see if red and green light beams are mixed. Write out the equations used on a sheet of paper and then record your prediction in the space provided on a chart similar to Figure 38.

Now hold a red filter in front of one light source and a green filter in front of the other light source. Aim part of one beam onto the screen so that it falls on part of the other beam. Notice the color where the red and green beams meet. Record the color you see.

Color of Light Beams	Color of Mixed Light	
	Prediction	Observation
Red and Green		
Red and Blue		
Green and Blue		
Red + Green + Blue		

ADDING LIGHT BEAMS
Fig. 38

Predict the colors that you will see by mixing the other pairs of colored beams listed in the chart. Write out equations for each prediction, then turn all this in to your teacher for evaluation. Try mixing these beams and record your observations.

Using a third light source, mix part of a blue beam with part of a red beam and part of a green beam. Make a drawing of the three beams and name each color you see in the drawing you make.

The major effects of trichromatic[*] additive mixing are shown in the diagram on the next page (Figure 39). Make a copy of the diagram on a separate sheet of white paper and color the diagram as indicated.

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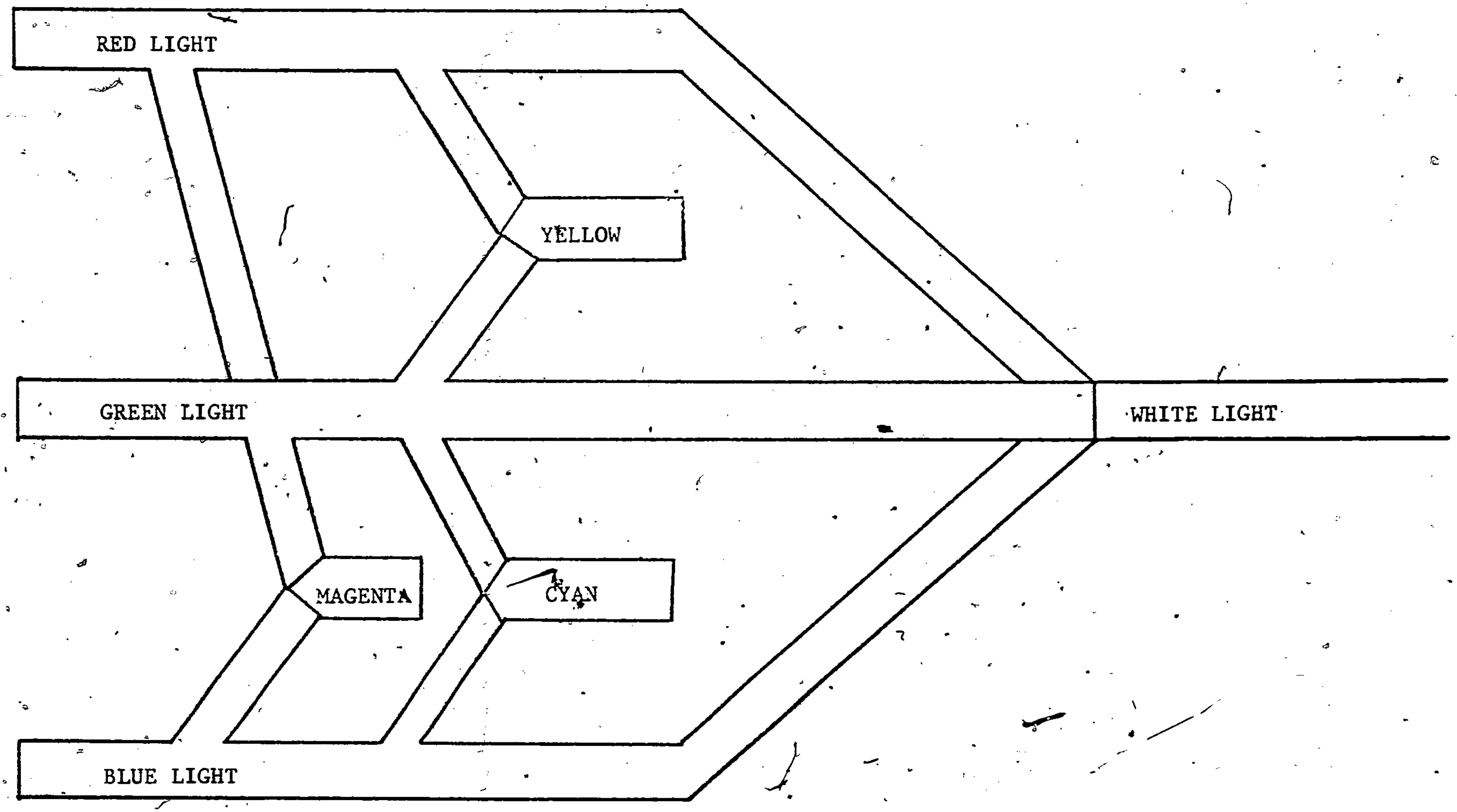
* Trichromatic simply means "3-color".



TRICHROMATIC ADDITION OF LIGHTS
Fig. 39

It should be obvious that the greater the number of colored lights which are mixed by addition, the brighter and the nearer to white the results will be, so that as white is actually approached, the resulting colors will become paler or lighter tinted.

A straightforward example of the practical use of additive color mixing is the stage lighting in a theater; red, green and blue spotlights or floodlights are employed for theatrical lighting. Color photography and color television also use additive color mixing.

RESOURCE PACKAGE 11-1

SUBTRACTIVE COLOR MIXING

Unlike additive mixing which is based on the projection and blending of colored light, subtractive mixing involves colored materials (pigments), usually in the form of paints, inks or dyes. The name subtractive is used because the effects are obtained by combining materials which always absorb or subtract light.

In contrast to whiteness of lights as being the ultimate result of blending several colored lights (the presence of all colors), the end result of mixing a sufficient number of colored substances is black (the absorption of all colors).

Strictly subtractive mixtures take place only with transparent, non-scattering media, such as solutions of dyes and transparent printing inks. Paints and many printing inks contain opaque finely-divided insoluble pigment particles suspended in fluids; and these particles scatter the light by multiple reflections, making color mixing more complicated.

Let us consider the following example. If a yellow paint (which reflects mainly red, orange, yellow and green light and absorbs mostly blue and violet light) is mixed with cyan paint (which reflects mainly violet, blue and green light and absorbs mostly yellow, orange and red light) the result is green, because this is the only light reflected by both paints, all other colors being absorbed. If a red paint which absorbs green light is added to this mixture, the final product is black because of the total subtraction of light.

By using again the simple notation of initial letters, W = R + O + Y + G + B + V, we can put an X in the proper position to indicate the absorption of light of a certain color. The yellow paint would then be represented by R + O + Y + G + X + X. Let's see how to write the representation for cyan and red paint:

Mixing produces:

Yellow Paint = R + O + Y + G + X + X
Cyan Paint = X + X + X + G + B + V

Mixture = X + X + X + G + X + X (green)
\+
Red Paint = R + O + X + X + X + X

Mixture = X + X + X + X + X + X (black)

A limitation to the above notation is it does not indicate the quantity or proportion of light involved; quantity or proportion of light would indicate the lightness or brightness of material.

It is often thought that red and blue materials result in purple. If the notation for blue paint were X + X + X + G + B + V; what would be the result of a mixture or red and blue paint? (On a seperate sheet, write out a notation such as the one shown above.)

To obtain a purple (a blue-violet) effect, it is necessary to mix blue or cyan with magenta paint:

Cyan Paint = X + X + X + G + B + V
Magenta Paint = R + O + X + X + B + V

Mixture = X + X + X + X + B + V (Bluish-violet)

A careful mixing of various proportions and combinations of yellow, cyan and magenta paints will produce all possible colors except white. Materials having these three colors (yellow, cyan and magenta) are often referred to as subtractive or primary pigment colors. These primaries may sometimes be known as the downward working primaries since, when mixed, the resultant color approaches blackness rather than whiteness.

The third binary* mixture from three primary colored paints is that of yellow and magenta:

Yellow Paint = R + O + Y + G + X + X
\+
Magenta Paint = R + O + X + X + B + V
=
Mixture = R + O + X + X + X + X (orange-red)

The mixing of yellow and magenta subtractive primaries results in red-orange or essentially, red. Yellow mixed with cyan results in green or yellow-green, if the cyan reflects any light; and magenta mixed with cyan gives blue-violet or, essentially, blue. The resulting colors of this paragraph (red, green and blue) are the subtractive secondary colors. The subtractive secondaries correspond in notation to the additive primaries; and if we refer to the colors produced by the binary mixture from the three additive primaries

---

*Binary means using only two colors.

as additive secondaries, which are yellow, magenta and cyan, they correspond to the subtractive primaries. Therefore, the additive and subtractive primaries may be said to be complementary to each other. (See Figures 40 and 41).

PRIMARIES	
Additive	Subtractive
Red	Yellow
Green	Magenta
Blue	Cyan

PIGMENT PRIMARIES
Fig. 40

SECONDARIES	
Additive	Subtractive
Yellow	Red
Magenta	Green
Cyan	Blue

PIGMENT SECONDARIES
Fig. 41

The relationship between the additive and subtractive primaries is important. Processes of subtractive color reproduction employ the yellow, magenta and cyan primaries; which, at first glance, seem to be different from the red, blue and green lights used in additive mixing, but the subtractive yellow primary removes all blue and violet from white light, the magenta absorbs yellow and green, and the cyan suppresses red and orange light. Since all colors can be produced by additive mixtures in various proportions of red-orange (red), yellow-green (green) and blue-violet (blue) lights, it follows that the subtractive primaries acting as absorbers of red, green and blue light may be regarded as controls for the red, green and blue parts, or thirds, of white light. By changing the amounts of the subtractive primaries on a white surface, the intensities of the primary red, green and blue proportion of the reflected white light are altered and a wide range of colors can be produced. Both the subtractive and additive methods are actually based on the same principle and linked with the triple characteristic of color vision, although the two methods differ in manner.

Now that the two systems have been connected, it may be helpful to use the nomenclature of white minus red, green and blue, the minus sign inserted respectively to show the absorbed third of the spectrum.

$$\begin{array}{ll} \text{Yellow Primary} & = W - B = R + G - B \\ \quad + & \\ \underline{\text{Cyan Primary}} & \underline{= W - R = -R + G + B} \\ \text{Mixture} & = W - B - R = G \text{ (green)} \end{array}$$

Yellow Primary = W - B = R + G - B
\+
Magenta Primary = W - G = R - G + B

Mixture = W - G - B = R (red)

Magenta Primary = W - G = R - G + B
\+
Cyan Primary = W - R = -R + G + B

Mixture = W - G - R = B (blue)

Now complete the following on a separate sheet of paper:

Yellow Primary = ____________ = ____________
\+
Magenta Primary = ____________ = ____________
\+
Cyan Primary = ____________ = ____________

Mixture = ____________ = ____________

INVESTIGATING PIGMENT COLOR SUBTRACTION:

You will need:

- 3 colors of tempera paint powder (yellow, cyan and magenta).
- 750 ml beakers
- balance
- stirring rod
- small paint brush

Place one gram of yellow paint powder in a beaker. Do the same for the cyan and magenta paint powder. Now add 3 ml of water to each beaker, stir and observe the colors.

Now place one gram of yellow and one gram of magenta in a beaker. Add 6 ml of water to the beaker, stir and observe the color. Do the same for a yellow-cyan combination and a cyan-magenta combination. Enter your results in a chart similar to Figure 42.

In the last beaker, add one gram of both yellow, cyan and magenta. Add 9 ml of water, stir and record your results.

Paint Colors	Color of Mixture
Magenta + Yellow	
Magenta + Cyan	
Yellow + Cyan	
Yellow + Cyan + Magenta	

MIXING PAINTS
Fig. 42

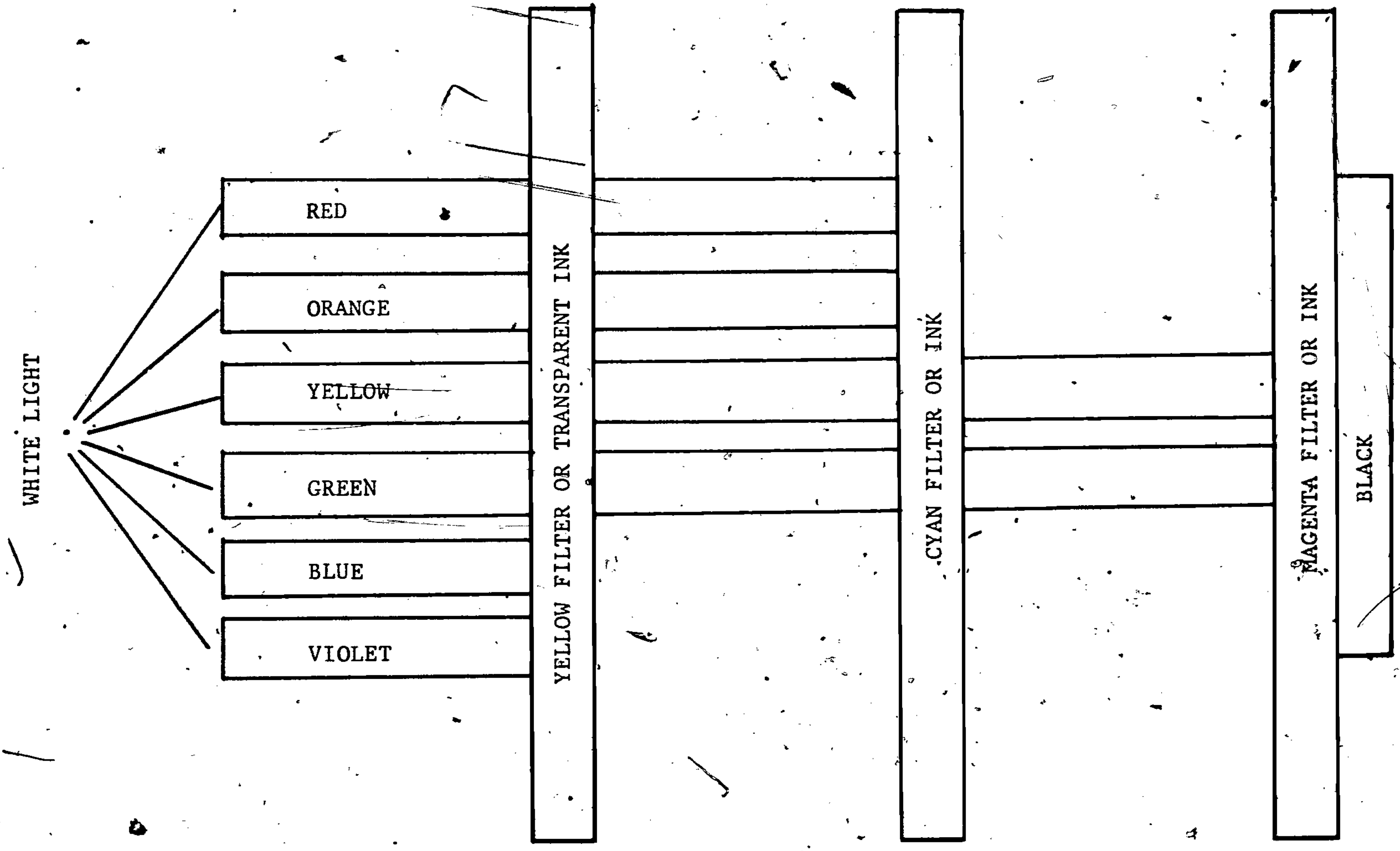
Are the results of a mixture of cyan, magenta and yellow paint as you would have predicted? Explain.

Glass filters can also be used to demonstrate the subtractive method. If three transparent glass filters having yellow, magenta and cyan colors of the subtractive primaries are placed one behind the other in the path of a beam of white light, each will absorb one third of the components of the light so that no light will emerge from the last of the three filters and the end effect will be blackness.

Although three filters of the subtractive primaries are needed, there need be only two filters of the additive primaries to accomplish the same thing. (You might want to try this!)

The principle of the method of using transparent materials is illustrated on the next pate. Make a copy of the diagram on a separate sheet and color Figure 43 as indicated.

Because the subtractive method is easier to apply, it is more generally used than/the additive method and is used in art works, in modern color photography, in cinematography and in all branches of the painting industry.



TRANSPARENT SUBTRACTIVES
Fig. 43

TEST

I. MULTIPLE CHOICE

1. The wavelength of visible light is about

   a) .00005 cm   b) 20 to 30 cm   c) 186,000 miles   d) 5×10^{14} = 500,000,000,000,000 cm

2. The speed of light is

   a) always 186,000 miles/sec
   b) 186,000 miles/sec in vacuum and less through some matter
   c) can't say as all colors always have different speeds

3. Normally all stars look white (or almost so) to our eyes because

   a) they all are white, having color mixtures like our sun
   b) they are too dim to "fire" the cones on our retina
   c) our retina has only rods, no cones

4. If you stare at a bright yellow object for 15 or so seconds and then quickly change your eyes to look at a white screen, you seem to see a

   a) yellow afterimage
   b) purple afterimage
   c) green afterimage
   d) black afterimage

5. Light is conveniently understood from a

   a) wave model
   b) particle model
   c) both, or a combination thereof
   d) neither

6. Different colors of light necessarily have

a) different speeds
b) different wavelengths
c) different intensities or amplitudes or brightnesses

7. A red rose with green leaves when placed in red light seems to you to have

a) red flower and red leaves
b) red flower and green leaves
c) red flower and black leaves
d) green flower and red leaves
e) green flower and green leaves
f) green flower and black leaves
g) black flower and red leaves
h) black flower and green leaves
i) black flower and black leaves

8. Suppose you write some green words on a white paper. When illuminated with green light the words and paper respectively look

a) green and white
b) green and green
c) black and green
d) black and black

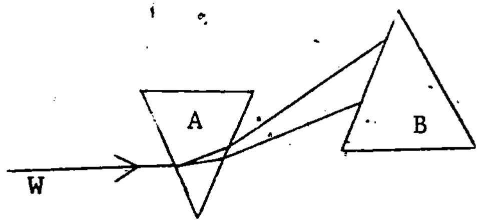
9. Refraction (bending of a light beam or ray as the light makes a nonperpendicular passage from one medium to another) is caused by

a) the very small wavelength of light
b) the speed of light being different in the two media
c) the fact that the light is partially transmitted and partially reflected

10. We know red light has a longer wavelength than blue and violet. Hence red has a lower frequency. You might even like to say it has less "interaction" with glass or water as the light passes through. So you would conclude that

a) red light refracts more than blue
b) red refracts less
c) both refract exactly the same amount

11. Suppose white light goes through prism A and separates into the full spectrum. What happens after prism B?



a) light recombines
b) the spectrum separates twice as much
c) the light is totally reflected back to the first prism
d) other (explain)

12. Red light has a longer wavelength than blue. Hence a grating deflects the red light through

a) a greater angle than the blue light
b) a smaller angle than the blue light
c) the same amount as the blue light, exactly

13. Which of the following is the best proof that light has wave properties?

a) separation of colors by a prism
b) refraction of a laser beam at an air-water boundary
c) overlapping of two color filters producing a new color
d) looking at a filament light and seeing a pattern of lights through a grating

14. The fact that AM radio waves do not form sharp shadows when passing by solid objects proves

a) their wavelength is long compared to visible light
b) they penetrate better than light through solid objects
c) they are really particles, not waves

15. The colors seen in a floating soap-bubble are due to

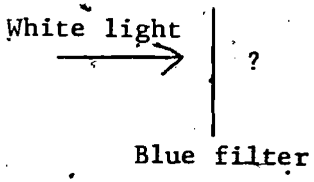
a) refraction and prism effects
b) grating or diffraction effects
c) interference effects

16. A razor blade in a laser beam does not cast a sharp shadow because of

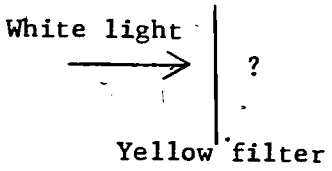
a) reflection off the sharpened edge
b) refraction and speed changes near the edge
c) slowing down the light as it passes through the thin metal
d) wave diffraction around the sharp edge

II. VERY SHORT ANSWERS

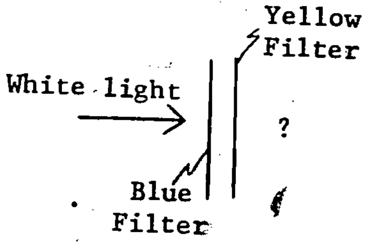
1. White light shines on a blue filter. What color(s) are transmitted through?



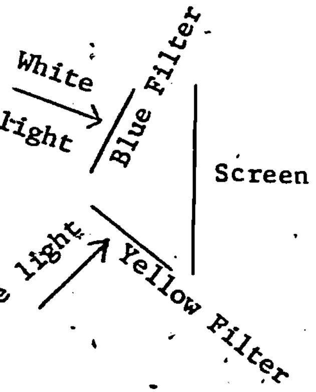
2. White light shines on a yellow filter. What color(s) are transmitted through?



3. Remember your answers to 1 and 2. If white light now shines through the two filters, placed back-to-back, what color(s) come through?



4. Remember your answers to 1 and 2. If two beams of white light are shined onto a white screen, one through a blue filter, one through a yellow one, what color do you see on the screen?



III. YOUR TEACHER SPEAKS !

1. There is a maximum of energy in the solar radiation spectrum. At about what wavelength or equivalently at what color does it occur? If the sun were to suddenly become cooler, would this maximum shift toward the red or toward the blue (region) of our vision?

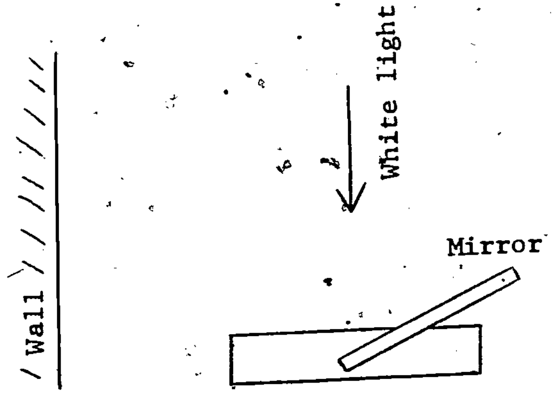
2. Students are occasionally surprised to find out that there is a wealth of color in the stars. This is not surprising to us, however, because there is no reason to expect that all the stars we see are burning at the same temperature as our sun. Remembering what we know about the human retina, please explain why the stars all look quite white to us.

3. I understand that primates and a kind of ground squirrel are the only mammals that have cones on the retina. Explain whether or not a bullfighter is obliged to wave a RED flag at the bull she is fighting.

4. We can overlap blue, green and red light beams on a screen, and the result is a pretty white screen. Why is it that if you mix blue, green and red paints, you do not get white paint?

5. Suppose that you take a beam of white sunlight and separate it into its many colors using a prism. Suppose further that you isolate just the green part of this spectrum. Now finally suppose that you put a red rose with green leaves in this green light. What color does the flower look to you? How about the leaves? Does the flower or the leaves heat up more?

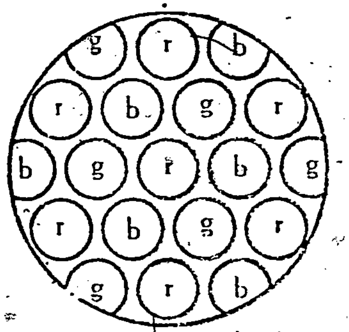
6. One of the simple pleasures in life is to place prisms on your windowsills and observe the color spectra inside your house on sunny days. If you do not have a glass prism, you should be able to make one like the one I have sketched out of a mirror, a dish like an ice tray and some water. For simplicity, let's suppose that white sunlight is coming straight down on my "prism". Please sketch the blue and red rays as they enter the water, hit the mirror, cross back over the water-air boundary, and strike the wall. Will the spectrum on the wall have red on the top or on the bottom? Try this experimentally to check your answer.



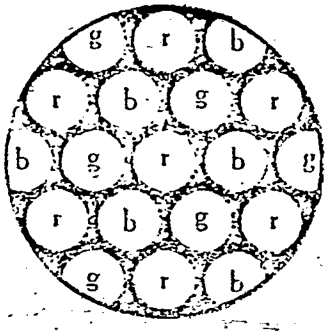
IV. 1. A recent scientific journal published a research report relating elementary school pupil problems to fluorescent classroom lights. When removed from these lights, hyperactive problem children behaved normally again. Discuss briefly some effects (of which you are aware) of lights and color upon people.

2. A red and blue flowered begonia, with green stem and leaves, is illuminated by red light. Describe its apparent color.

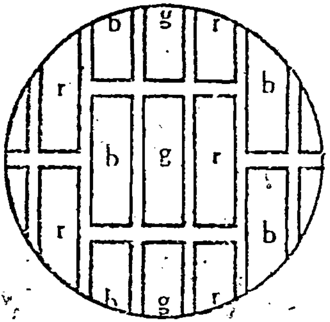
V. Trace the following figures onto a sheet of white paper. Follow the instructions below, and you'll learn something about color TV.



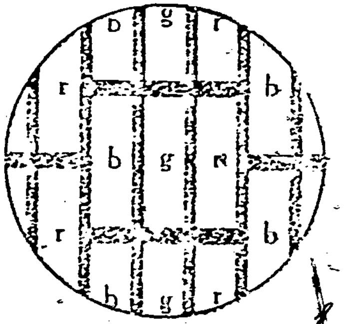
1



2



3



4

Get a box of crayons and take out three colors: red, blue, and green.

These are the three colors that make up a color television picture. If you took microscopic portions of color television screens, blew them up and simplified them, they would look like the diagrams above.

FIRST GENERATION COLOR TV

Color in the circles in the first diagram. Do not color the background.

You have just simulated the way the first generation of color TVs reproduced a color image. The colors look weak, soft.

This process was around back in 1956. Unfortunately, many color TVs on the market still use it today.

SECOND GENERATION COLOR TV

Using the same three colors, color in the second diagram. Compare the two.

The circles in the second diagram are much more colorful. Sharper. Clearer.

The reason? The jet black background.

This process is also being used by many manufacturers today; and while it may be far superior to generation I, to a color TV expert, it's practically ancient.

THIRD GENERATION COLOR TV

Now we come to the modern way of reproducing a color image. Stripes.

Again, do not color in the background. Notice how much more color you can get into stripes than circles--even though the total area of the diagrams is equal.

The colors look brighter, more true-to-life.

This system is one of the newest methods of reproducing a color image, but it's not the newest.

FOURTH GENERATION COLOR TV

When you color in the fourth diagram, you'll see it has all the advantages of the previous two:

(1) the wealth of color of a stripe, and (2) the sharpness and snap of a black background.

This results in the brightest, clearest color television image possible today.