SCIENCES EDUCATION FOUNDATION
GENERAL ATOMICS

It's a Colorful Life

February 26, 2002

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Author's Note

We live in a colorful world. Yet, a whole module devoted to exploring color? It might seem like a waste of time in a science curriculum where the basics of physics, chemistry, earth science, or biology could be taught. So why study this topic?

I think that the main reason is that this subject is relevant to everyone's daily life, no matter what interests you may have. Once you understand color theory, you know why objects have color, why colors change in different lighting, why the sun is yellow and the sky is blue, why your ink jet printer uses those three bright colors, how color is printed in magazines, why food packages have those colored squares on them, how your TV or computer monitor works, etc. Life is suddenly more interesting, more enriching, more understandable.

But is it good science? I think that there is no subject better suited to teaching the relationship between theory and experiment, between data and models, than color. Our earliest exposure to a model was probably that of the color wheel to explain and predict the mixing of paints. Interestingly, as you will see, that model was incorrect and the primary colors of paint that you were taught (red, yellow, and blue) are also incorrect. So this module will result in the learning of an important lesson in critical thinking - that models do change - and models, even those taught in school, are not always correct. Also students will see first hand how difficult it is to accept a new model, when we are comfortable with our old one. They can share the experience that others have had when the earth-centered solar system was replaced by the sun-centered solar system or when classical mechanics was replaced by quantum mechanics: even though the old model seemed to work, new data indicated that it wasn't right. And they will experience how many people (like their parents!) are reluctant to accept the new model.

What else is unique about this subject? Probably the wealth of ways in which it can be explored and understood as well as its multidisciplinary nature. As this module demonstrates, color theory is perfectly suited to inquiry-based science. Students perform a variety of experiments to develop an understanding of color and then generate a variety of pictures, tables, graphs, and mathematical expressions to model their data. Thus, students engage in realistic multidisciplinary science experiments, which involve taking careful measurements, modeling data, using a variety of mathematical tools, and applying their understanding to different subjects and situations. The variety and complexity of color models that students can explore are amazing.

How does this module relate to science that students should be taught, as expounded by the national consensus documents: Benchmarks for Science Literacy and the National Science Education Standards? There

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is an excellent correspondence. The relationships of this module to both sets of standards are explicitly described on the following pages. In addition, the relevant Benchmarks are denoted in boxes in the teacher's guide to aid teachers in emphasizing these important points during instruction.

These activities also utilize the science process skills that the National Science Education Standards call for:

- "Learning subject matter disciplines in the context of inquiry..."
- "Investigations over extended periods of time."
- "Using multiple process skills - manipulative, cognitive, procedural."
- "Doing more investigations in order to develop understanding, ability, values of inquiry and knowledge of science content."

While this module is aimed at middle school students, aspects of these experiments have been successfully used at levels ranging from elementary to college. Everyone finds color a fascinating subject - for we all truly live a colorful life!

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Foreword

This module arose out of a late-night discussion between my wife and me. My wife, Wendy, is a science (and art) consultant for our local elementary school. Our discussion involved the following question: If the primary colors of paint are red, yellow, and blue - and the primary colors for computer monitors are red, green, and blue - then why is there the switch from yellow to green. It seemed that the primary colors should all be the same or that they should all be different. My wife asked me if I knew why this is. Like a good Ph.D. physicist with years of graduate classes and industrial experience under my belt, I gave the good scientist answer: "I don't know - but I'm going to find out."

I realized that I had never been exposed to color mixing theory or experiments in my entire career, and really had no background in this area. This led to my examining many books and articles, in my collection as well as at the library, having discussions with my colleagues, and exploring the web for sites on color. What I found is that the subject of color is treated quite differently in different disciplines, and rarely does anyone discuss why their color theory differs from the others! For example, I have yet to find a physics text that shows a color wheel or that discusses why the "primary colors" for painting (red, yellow, blue) are different from the primary subtractive colors (cyan, magenta, yellow).

Briefly, here is what this module is about. In the first experiment students explore additive color mixing. Think of this as: how do you make colored light when you are in a dark room. To reiterate: you are starting in a dark room. If you want to make color, you have to add colored light. If you just have a red light shining in your eye in a dark room, you will see the color of the light as red. If you now add a green light to the red light, the lights add - and you end up seeing the color of the light as yellow. If you now add a blue light to the other two, the light will now appear to be white.

The way students can discover this for themselves is to look at a computer monitor using an 8X magnifier. If they look at a yellow square on the monitor, they will observe that it consists of tiny lights of red and green. If they look at the white part of the monitor, they will see that it consists of tiny lights of red, green, and blue.

In the next series of experiments, students explore subtractive color mixing. Think of this as: how do make colored objects when you are in a room that is filled with white light. To reiterate: you are starting in light room filled with white light. We can model this white light as being a combination of red, green, and blue light. If we want to make colored objects from this light, we must remove some part of that red, green, or blue light.

Imagine that white light passing through something that absorbs the blue light so that only the red and green parts of the white light are left.

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What color will we observe that object as? Well, since the red and green light will still remain, we will see that object as yellow - the result of red and green light striking our eye.

Now imagine that white light passing through something that absorbs the blue light and the green light so that only the red part of the white light remains. What color will we observe that object as? Well, since the red light will still remain, we will see that object as red.

In the second experiment of this module, students investigate the color of objects that absorb a single color of light. The third experiment involves the investigation of materials that absorb two colors of light. In the fourth experiment, students discover the colors that can be made by absorbing fractional amounts of light, which leads to an understanding of how color printing works - the focus of experiment 5. In experiment 6, students revisit these concepts in a slightly different way using overlapping colors rings and wheels.

Note that there are a large number of experiments and assessments in this module. You should choose those that you believe would work best for you. Good luck and please send me an e-mail (Larry.Woolf@gat.com) with your comments or suggestions.

I would like to thank the following people for their assistance in the development and refinement of this module: Wendy Woolf, Peter Kaiser, Roger Wynn, and the science teachers of San Diego county. I thank Virginia Deguitas for the masterful way in which she transformed my rough sketches of color materials into the works of art (actually works of color) that became the color wheel wall chart and the other color mixing materials. Finally, I would like to acknowledge the support and encouragement of Patricia Winter, Nancy Taylor, Anne Blue, Neal Blue, the General Atomics Sciences Education Foundation, and Professor Art Ellis of the University of Wisconsin.

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More Foreword:
To the Artist

To paraphrase Richard Nixon, "I am not an artist." So please realize that this unit is written from the point of view of an artistically challenged physicist (me).

If you are a typical artist, you are a free-spirit, unbound by the constraints of physics. You may think that the color wheel presented in this unit is wrong, since it is not the one used by all artists. But I only ask you to do the following: compare the colors that you can produce using cyan, magenta, and yellow to those that can be produced using red, yellow, and blue. I believe that you will find the gamut (range) of colors considerably larger if you use the former 3 colors compared to the latter. You might also convince yourself that the color wheel used in this module is not half bad!

If you are an elementary school art teacher, you are probably aware of the muddy colors that result from mixing red and blue - it's hard to get a decent bright purple. You might have thought that this was due to the poor quality of paints that you used. Not so. Try mixing cyan and magenta instead - you will be surprised at the vibrant purples that you can make. The difficulty has been due to the choice of red, yellow, and blue as your primaries. This set of colors produces a much smaller range of colors than cyan, magenta, and yellow.

Finally, mixing paint colors is much more complex than the simple subtractive color mixing described in this module. Paints may be transparent, opaque, or somewhere in between. You may be mixing transparent colors with opaque colors. The resulting color depends on many factors, including the size of the pigment particles, the chemical composition of the pigment, the nature of the medium used (water, oil, etc.) the presence of a hiding powder pigment, such as titanium dioxide, and the lighting. In addition, the mixed resultant color is often a result of both additive and subtractive color mixing. Chapter 11 in the reference <u>Light and Color in Nature and Art</u> has a nice discussion of this issue.

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Even More Foreword: To the Color Scientist

To paraphrase Richard Nixon, "I am not a color scientist." So what does a color scientist typically think about the approach used in this module. They generally think that this module uses a very simplified approach to color theory. They may also take issue with the use of terms such as "blue color" and "red light." The color scientist realizes that color is a human visual response. They know that the color of an object that we perceive depends on the light striking the object, the optical properties of the object, and the processing of the resultant light that enters our eye by the brain. They know that light is not “colored” – it consists of different wavelengths with different relative intensities; and that objects have no intrinsic “color” – they are defined by optical constants n and k and their thickness – or they may be defined by their optical absorption, reflection, and transmission spectra

Yet the advanced concepts discussed above are not accessible to the target audience of this module – middle and high school students or perhaps beginning college students. The use of colored light and colored objects are, I believe, useful models for the world around us. A useful model can explain and has predictive power. It also has limitations. The models used in this module can be used to predict the color of mixtures of light and pigments as well as to understand the color of semiconductors, the sun, sky, and stars. Their limitations are also pointed out throughout the unit.

The bases for understanding more advanced color concepts are here. The color wheel and complementary colors naturally lead into the CIE chromaticity diagram and the associated method for describing complementary colors. Color coordinate systems, such as xyYand L* a* b*, follow from using the RGB and CMY color coordinates introduced in this unit. Students will have learned that colors can be defined by 3 coordinates, which is true of all color models. Color math presented here leads to color math and color differences, such as delta E, that can be done using color coordinates. Hopefully, the color scientist will agree that this unit is appropriate for the target audience and lays a solid foundation for future studies of this fascinating topic.

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Color: An Overview

There are many methods for presenting and investigating color concepts.

- Verbal
- Written
- Pictorial
- Experimental
- Mathematical
- Computer

Color incorporates many diverse subject areas.

- Physics - Color Theory/Models; Changing “truth” of scientific models
- Math/Algebra - Color Math
- Math/Geometry - Color Wheels, Color Cube, Other color models
- Visual Arts- Color Mixing/Color Printing/Color Wheels (Mixing Paints)
- Computer Science - Color Monitors, TVs/Color Models
- Performing Arts - Stage Lighting (Mixing Colors of Light)
- Biology - Color Vision (Rods/cones/evolution of color vision)
- Earth Science - The color of the sky, sunsets, green flash
- Space Science - The color of stars and flames
- Chemistry - The color of plants, smog

Color can be taught at increasing levels of complexity, corresponding to the cognitive development of children.

- Identification of colors
- Compare the mixing of different “primary” colors of paint
- Investigation of printed colors using microscope
- Investigation of computer monitors using magnifying glass
- Experiments to investigate additive and subtractive color mixing using colored transparencies
- Color math to understand/predict color experiments
- The color wheel to understand/model/predict color experiments
- Sophisticated color models for understanding color, such as the RGB and CMY models
- More sophisticated color models, such as the RGB or CMY color cube, hue/saturation/value, etc.

The purpose of this module is to explore the color concepts and related subject areas delineated above using a wide variety of methods.

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Main Color Ideas

The main colors ideas explored in this unit are summarized below.

- The primary colors for light are red, green and blue.
- The primary colors for printing or for painting using transparent paints are cyan, magenta and yellow, not red, yellow and blue.
- The three primary colors can produce a wider range of colors than using any three other colors. No two primary colors can produce a third primary color.
- Complementary colors of inks or transparent paints that are printed on top of one another produce black.
- Complementary colors of light that overlap produce white.
    - Red and cyan are complementary colors.
    - Green and magenta are complementary colors.
    - Blue and yellow are complementary colors.
- Complementary colors appear across from each other in the color wheel; they do not appear this way in the traditional color wheel.
- No inks, paints, transparencies or color sources are perfect. The above statements are true for ideal materials, but only mostly true for normal materials.
- Human color vision is quite complex and is an area of much current research.

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Correspondence to the National Science Education Standards (NSES)

This unit relates to the following NSES physical science content standards in grades K-4:

Properties of Objects and Materials

- "Objects have many observable properties, including size, weight, shape, color, temperature, and the ability to react with other substances. These properties can be measured using tools, such as rulers, balances, and thermometers."

Light, Heat, Electricity, and Magnetism

- "Light travels in a straight line until it strikes an object. Light can be reflected by a mirror, refracted by a lens, or absorbed by the object."
- "Light interacts with matter by transmission (including refraction), absorption, or scattering (including reflection). To see an object, light from that object- emitted by or scattered from it - must enter the eye."

This unit relates to the following NSES physical science content standards in grades 5-8:

Transfer of Energy

- "Energy is a property of many substances and is associated with heat, light, electricity, mechanical motion, sound, nuclei, and the nature of the chemical. Energy is transferred in many ways."
- "Light interacts with matter by transmission (including refraction), absorption, or scattering (including reflection). To see an object, light from that object- emitted by or scattered from it - must enter the eye."

This unit relates to the following NSES physical science content standards in grades 9-12:

Conservation of Energy and the Increase in Disorder

- "The total energy of the universe is constant. Energy can be transferred by collisions in chemical and nuclear reactions, by light waves and other radiation, and in many other ways. However, it can never be destroyed. As these transfers occur, the material involved becomes steadily less ordered."

Interaction of Energy and Matter

- "Waves, including sound and seismic waves, waves on water, and light waves, have energy and can transfer energy when they interact with matter."

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Correspondence to the Benchmarks for Science Literacy

Throughout this module, relevant Benchmarks for Science Literacy are noted. The Benchmarks can be used by the teacher as an indication of a key science concept that can be emphasized during that particular investigation. They could also be used as an assessment tool by the teacher by turning the Benchmark into a question such as: Describe how the activity that you just performed is related to the following Benchmark.

These Benchmarks are just a guide. Other Benchmarks may be relevant to this module. Only parts of some of the Benchmarks quoted may be relevant to the material. Some of the Benchmarks quoted may be relevant to other sections in the module. Teachers can use the Benchmarks as a guide to appropriate curriculum for their particular grade level.

The following listing shows the relevant Benchmarks and where they are referenced.

p. 38
Benchmark 4F 8th grade: *"Something can be 'seen' when light waves emitted or reflected by it enter the eye-just as something can be 'heard' when sound waves from it enter the ear."*
Benchmark 4F 8th grade: *"Human eyes respond to only a narrow range of wavelengths of electromagnetic radiation-visible light. Differences of wavelength within that range are perceived as differences in color."*

p. 40
Benchmark 9B 5th grade: *"Tables and graphs can show how values of one quantity are related to values of another."*
Benchmark 9B 12th grade: *"Tables, graphs, and symbols are alternative ways of representing data and relationships that can be translated from one to another."*
Benchmark 11B 12th grade: *"The basic idea of mathematical modeling is to find a mathematical relationship that behaves in the same ways as the object or processes under investigation. A mathematical model may give insight about how something really works or may fit observations very well without any intuitive meaning."*

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Benchmark 1B 2nd grade*: "Tools such as thermometers, magnifiers, rulers, or balances often give more information about things than can be obtained by just observing things without their help."*

Benchmark 12D 8th grade*: "Students should be able to organize information in simple tables and graphs and identify relationships they reveal."*

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Benchmark 4A 12th grade*: "The stars differ from each other in size, temperature and age, but they appear to be made up of the same elements that are found on the earth and to behave according to the same physical principles. Unlike the sun, most stars are in systems of two or more stars orbiting around each other."*

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Benchmark 11B 8th grade*: "Different models can be used to represent the same thing. What kind of model to use and how complex it should be depends on its purpose. The usefulness of a model may be limited if it is too simple or if it is needlessly complicated. Choosing a useful model is one of the instances in which intuition and creativity come into play in science, mathematics, and engineering."*

Benchmark 11B 12th grade*: "The usefulness of a model can be tested by comparing its predictions to actual observations in the real world. But a close match does not necessarily mean that the model is the only 'true' model or the only one that would work."*

Benchmark 12D 8th grade*: "Students should be able to read simple tables and graphs produced by others and describe in words what they show."*

Benchmark 12D 8th grade*: "Students should be able to find and describe locations on maps with rectangular and polar coordinates."*

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Benchmark 11B 8th grade*: "Mathematical models can be displayed on a computer and then modified to see what happens."*

Benchmark 11B 12th grade*: "Computers have greatly improved the power and use of mathematical models by performing computations that are very long, very complicated, or repetitive. Therefore computers can show the consequences of applying complex rules or of changing the rules. The graphic capabilities of computers make them useful in the design and testing of devices and structures and in the simulation of complicated processes."*

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Benchmark 4F 8th grade: *"Light from the sun in made up of a mixture of many different colors of light, even though to the eye the light looks almost white. Other things that give off or reflect light have a different mix of colors."*

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Benchmark 4E 8th grade: *"Energy cannot be created or destroyed, but only changed from one form into another."*

Benchmark 4E 8th grade: *"Most of what goes on in the universe-from exploding stars and biological growth to the operation of machines and the motion of people-involves some form of energy being transformed into another. Energy in the form of heat is almost always one of the products of an energy transformation."*

Benchmark 4E 8th grade: *"Heat can be transferred though materials by the collisions of atoms or across space by radiation. If the material is fluid, currents will be set up in it that aid the transfer of heat."*

p. 83, 94

Benchmark 9B 12th grade: *"Any mathematical model, graphic or algebraic, is limited in how well it can represent how the world works. The usefulness of a mathematical model for predicting may be limited by uncertainties in measurements, by neglect of some important influences, or by requiring too much computation."*

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Benchmark 4F 8th grade: *"Human eyes respond to only a narrow range of wavelengths of electromagnetic radiation-visible light. Differences of wavelength within that range are perceived as differences in color."*

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Benchmark 4D 2nd grade*: "Objects can be described in terms of the materials they are made of (clay, cloth, paper, etc.) and their physical properties (color, size, shape, weight, texture, flexibility, etc.)."*

Benchmark 4D 5th grade*: "Materials may be composed of parts that are too small to be seen without magnification."*

Benchmark 4D 5th grade*: "When a new material is made by combining two or more materials, it has properties that are different from the original materials. For that reason, a lot of different materials can be made from a small number of basic kinds of materials."*

Benchmark 11A 2ndgrade*: "Most things are made of parts."*

Benchmark 11A 5 th grade*: "In something that consists of many parts, the parts usually influence one another."*

Benchmark 11A 12th grade*: "A system usually has some properties that are different from those of its parts, but appear because of the interaction of those parts."*

Benchmark 11B 8th grade*: "Models are often used to think about processes that happen too slowly, too quickly, or on too small a scale to observe directly, or that are too vast to be changed directly, or that are potentially dangerous."*

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Benchmark 11B 2nd grade*: "A model of something is different from the real thing but can be used to learn something about the real thing."*

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Learning Cycle Guide to Experiments

Many educators and cognitive scientists believe that it is useful for teachers to utilize the learning cycle. The learning cycle incorporates the following 4 phases for an investigation: focus, explore, reflect, and apply. The table below indicates how the learning cycle approach is used in each of the experiments in this module. This table can assist teachers in developing lesson plans for each of these experiments

Learning Cycle	**Focus**	**Explore**	**Reflect**	**Apply**
Experiment 1: Light Emitting Colors and Their Color Mixing	Have students discuss what they know about colors of light.	Students explore how colors on a computer monitor are made.	Students develop a table of additive color mixing and a color wheel.	Students investigate how colors are made on a TV screen, the color of stars, sky, sun, and sunsets.
Experiment 2: Colors that Absorb Light	Have students discuss what they know about how we perceive the color of objects.	Students explore which colors of light are absorbed by different colors of transparent films.	Students determine why colored lights change when different colored films are placed in front of the lights and summarize their data in a table.	Students apply this knowledge to understanding the color of water, plants, smog, and how different colored clothing affects how hot you are.
Experiment 3: Overlapping CMY and their Complementary Colors	Have students predict what will happen when they overlap two transparent films of different colors.	Students explore the colors that result when they overlap two transparent films of different colors.	Students explain why certain colors are obtained when they overlap transparent films of different colors and summarize their data in a table and in a color wheel.	Students discuss why the correct primary colors are cyan, magenta, and yellow, not red, yellow, and blue. The also examine the complementary color seen in an afterimage.

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Learning Cycle	**Focus**	**Explore**	**Reflect**	**Apply**
Experiment 4: Overlapping gradients of CMYK	Have students predict how they can make colors other than red, green and blue, such as browns and oranges, by overlapping films of cyan, magenta, and yellow.	Students explore the colors that result when they overlap two or more transparent gradient films of cyan, magenta, yellow, and black.	Students discuss how a large range of colors can be produced using different color densities of cyan, magenta, yellow, and black transparent films and how printers use these colors for printing.	Students develop models to represent color printing.
Experiment 5: Color Printing using CMYK	Have students predict how colored pages are printed.	Students use handheld microscopes to investigate color printing.	Students tabulate how different densities of cyan, magenta, yellow, and black dots are used to produce different printed colors.	Students summarize their understanding of how color printing is done and relate it to color ink jet printers. They investigate the similarities between color printing and color photography.
Experiment 6: Mixing RGB or CMY Colors with the Color Wheel	Have students predict what concepts they could demonstrate using transparent color wheels and single color rings.	Students investigate complementary colors and a different way of demonstrating color mixing using color wheels and solid color rings.	Students discuss how artists choose pigments that they can use to prepare a palette of colors.	Students investigate the implications of this experiment for mixing paint colors and apply what they have learned to investigate why

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				the traditional color wheel is incorrect.

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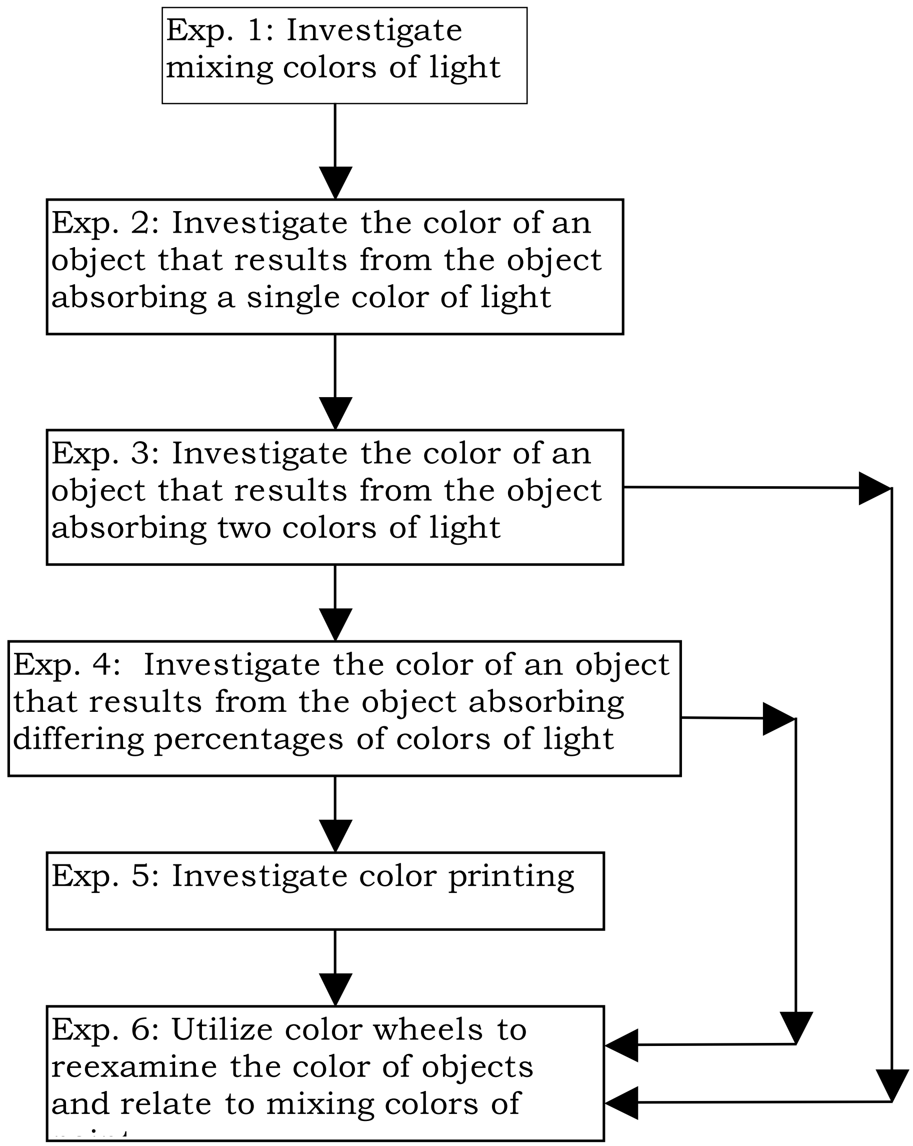
Logical Construction of Module



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Suggestions for Grade Level Concepts to Guide Instruction

Experiment	Grades K-2	Grades 3-5	Grades 6-8	Grades 9-12
1. Light Emitting Colors and Their Color Mixing	Identify colors of lights with magnifier	Use a table to summarize light mixing	Light waves entering our eyes allow colors to be seen	Representing results using tables, models, and symbols
2. Colors that Absorb Light	Identify colors of films	Identify which colors of light are absorbed by the film	Reflected light waves entering our eyes allow colored objects to be seen	Representing results using tables, models, and symbols
3. Overlapping CMY and Their Complementary Colors	Identify colors of overlapping films	Use a table to summarize results of overlapping films	Explain how subtractive color mixing occurs	Compare experimental results with computer and other math models
4. Overlapping gradients of CMYK	Identify colors of overlapping films	Describe effect of overlapping gradient colors	Explain how gradient colors can produce large range of colors	Discuss how these gradient strips model how color printing is done
5. Color Printing Using CMY	Identify colors and forms of printed material with microscope	Describe how colors can be made by combining small dots of different colors	Explain how CMY model predicts how color printing works	Investigate relationship between color printing and color photography
6. Mixing RGB or CMY Colors With the Color Wheel	Identify colors resulting from the overlapping experiments	Describe and organize results of mixing colors	Explain how CMY model is related to color wheel model	Investigate and compare the many different color models that are used

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Experiment 1:
Light Emitting Colors and their Color Mixing
(Student Activity Worksheet)

Materials Needed:

1. Color computer monitor/computer (1 per group of 2-4)
2. 8 X magnifying glass (1 per group of 2-4)
3. Color painting or drawing software

Procedure:

As a class

1. a. Discuss what you know about colors of light and what happens when you mix colors of light.

b. Draw and label the color wheel as you remember it. Describe in writing how you can use the color wheel to predict color mixing. Does the color wheel describe how paint colors mix, how printers mix colors, how colors of light are mixed, or some combination thereof?

In groups of 2-4

2. Using graphics software, produce solid squares of black, white, red, green, blue, cyan, magenta, and yellow on the computer monitor. Produce solid squares of five different shades of gray as well.
3. Using the magnifying glass, look at how black, white, red, green, blue, cyan, magenta, yellow and gray scales are produced by the color monitor.
4. a. Prepare 2 tables summarizing these results: one for the colors and one for the gray scales. Are they in agreement with your ideas you discussed in step 1a?

b. Use math (hint: think addition) to describe how white, yellow, cyan, and magenta were made.

c. Using colored arrows to describe how white, yellow, cyan, and magenta were made.

5. Draw a color wheel to represent your results. Discuss how it relates to the color wheel you drew in step 1b.
6. a Predict how the colors orange, dark green, and light green would be made. Discuss the applicability of the color wheel as a model for these colors.

b. Make an orange, dark green, and a light green object on the computer screen and observe how the color was made. Discuss how your predictions agree with your observations.

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As a class

7. Based on these results predict how colors and motion are made on a TV screen. Examine a TV set with the magnifier and determine if your prediction is in agreement with your data.

Assessment:

1. The sun is a white star. As the sunlight enters the atmosphere from overhead, the blue part of the sunlight is scattered in all directions, but the other parts of the light pass through unscattered.
   a. What color will the sun appear? Draw a diagram explaining why.
   b. What color will the sky appear? Draw a diagram explaining why.

2. When sunlight enters the atmosphere near the horizon, it passes through much more air before it arrives at your eye. This additional atmosphere scatters not only the blue, but also the green light. Using a diagram, explain, why this causes red sunsets.

3. As objects like stars, flames or light bulb filaments become hotter, their color changes.
   a. When cold, they give no visible light, only infra-red light.
   b. When warm, the only visible light they give off is red light.
   c. When they become hotter, the only visible light they give off is red and green light.
   d. When they become even hotter, the only visible light they give off is red, green, and blue light.
   e. When they become yet hotter, the only visible light they give off is green, and blue light.
   f. When they are hottest, the only visible light they give off is blue light.
   g. When they are extremely hot, they give off no visible light, only ultra-violet light.

Based on the above information, list the color of objects from coolest to hottest.

4. Develop an x-y graph, where x is the amount of red and y is the amount of green, that is a model for how red and green light mix. Label your axes and plot at least 6 data points. Label the coordinates of the data and describe their color. What are the limitations of this model?

5. Develop an x-y graph, where x is the amount of green and y is the amount of blue, that is a model for how green and blue light mix. Label your axes and plot at least 6 data points. Label the coordinates of the data and describe their color. What are the limitations of this model?

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6. Develop an x-y graph, where x is the amount of blue and y is the amount of red, that is a model for how blue and red pigments mix. Label your axes and plot at least 6 data points. Label the coordinates of the data and describe their color. What are the limitations of this model?

7. Develop a color cube that represents the colors that can be made by mixing red. green, and blue light.

8. Draw pictures that show how a computer monitor makes the following colors:

a. black	d. blue	g. yellow	j. orange
b. red	e. cyan	h. white	
c. green	f. magenta	i. gray	

9. As the "band gap" of a semiconductor increases, its color changes. Determine the color of semiconductors of increasing band gap using the following information.

a. A small band gap semiconductor absorbs red, green, and blue light.

b. Increasing the band gap causes the semiconductor to absorb only the higher energy green and the blue light.

c. Increasing the band gap even more causes the semiconductor to absorb only the high energy blue light.

d. Large band gap semiconductors don't absorb any visible light.

10. As the "band gap" of a semiconductor increases, the colored light that it can emit changes. Determine the color of light that semiconductors of increasing band gap can emit using the following information.

a. A small band gap semiconductor does not emit any visible light.

b. Increasing the band gap causes the semiconductor to emit only low energy red light.

c. Increasing the band gap more causes the semiconductor to emit only higher energy green light.

d. Increasing the band gap even more causes the semiconductor to emit only high energy blue light.

11. As the energy level spacing of a material increases, its color can change due to its absorbing some of the incident white light. Determine the color of a material as its energy level spacing increases using the following information.

a. At a small energy level spacing, the material only absorbs the low energy red light.

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b. At a medium energy level spacing, the material only absorbs the medium energy green light.

c. At a high energy level spacing, the material only absorbs the high energy blue light.

12. As the energy level spacing of a material increases, its color can change due to its emitting light. Determine the color of a material as its energy level spacing increases using the following information.

a. At a small energy level spacing, the material only emits the low energy red light.

b. At a medium energy level spacing, the material only emits the medium energy green light.

c. At a high energy level spacing, the material only emits the high energy blue light.

13. On the moon, there is no atmosphere.

a. If you were on the moon, what would be the color of the sun. Explain your reasoning.

b. If you were on the moon, what would be the color of the sky. Explain your reasoning.

14. More correctly, scattering of light by the atmosphere is gradual as well as selective: greatest at the blue end of the spectrum, least at the red end. The blue part of the incident light is scattered about 10 times more than the red part of the spectrum.

a. What will be the color of the sun for an atmosphere much denser than ours? Will the sun appear brighter or dimmer than ours? (Assume that the atmosphere does not absorb any of the incident light.)

b. What will be the color of the sky for an atmosphere much denser than ours? Will the sky appear brighter or dimmer than ours? (Assume that the atmosphere does not absorb any of the incident light.)

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Experiment 2:
Colors that Absorb Light
(Student Activity Worksheet)

Materials Needed:

1. Color computer monitor/computer (1 per group of 2-4)
2. 8X magnifier (1 per group of 2-4)
3. Transparent films of cyan, magenta, yellow, red, green, and blue

Procedure:

As a class

1. Discuss what you know about how we see the colors of objects. What is the color of the light that illuminates a room? What is the color of an object in the dark? Is the color of an object due to colored light that is given off by object or is it due to the color of the light that is reflected by the object?

In groups of 2-4

White room light reflecting off of white paper can be used as a white light source. By placing a red film over the paper, this is now a source of red light (if you see an object as red, it means that only red light is entering your eye - it is a red light source!) Placing green film over the paper produces a green light source. Placing a blue film over the paper produces a blue light source. In the experiments below, you will determine which primary color of light cyan, magenta, and yellow absorb.

2. Using the red light source described above, determine if cyan, magenta, or yellow absorbs the red light. (Hint: if you have a red light and an object that absorbs the red light is placed in front of the red light source, what color will the red light source appear to be?)
3. Using the green light source described above, determine if cyan, magenta, or yellow absorbs the green light.
4. Using the blue light source described above, determine if cyan, magenta, or yellow absorbs the blue light.

As a class

5. Now, one at a time, place each of the colored films on top of a white sheet of paper. What color does the white paper appear. Draw a diagram describing what is happening to make the paper appear that color.

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Continue in groups of 2-4:

1. Examine a white part of the computer monitor.

a. Place the cyan colored film on the monitor. What color does that part of the monitor now appear?

b. Using the magnifier, notice which dot colors now look black or much darker. It is helpful to look at the edge of the film using the magnifier so that you can see uncovered regions as well as regions of the monitor covered by the film. Try using both single and double thickness films to help make your determination.

c. From your observations, what can you conclude about how you see a cyan-colored object that is illuminated by white light?

d. Describe your observations using a math equation (hint: think subtraction), a table entry, and a diagram.

2. Repeat step 2 using the magenta film.
3. Repeat step 2 using the yellow film.
4. Repeat step 2 using the red film.
5. Repeat step 2 using the green film.
6. Repeat step 2 using the blue film.

Using some graphics software, produce solid squares of red, green, blue, cyan, magenta, and yellow on the computer monitor. For each situation below, perform the experiment described and explain why you see the resulting color using either words or a diagram.

7. Place at least 2 layers of cyan film over the red square.
8. Place at least 2 layers of cyan film over the green square.
9. Place at least 2 layers of cyan film over the blue square.
10. Place at least 2 layers of cyan film over the cyan square.
11. Place at least 2 layers of cyan film over the magenta square.
12. Place at least 2 layers of cyan film over the yellow square.
13. Place at least 2 layers of magenta film over the red square.
14. Place at least 2 layers of magenta film over the green square.
15. Place at least 2 layers of magenta film over the blue square.
16. Place at least 2 layers of magenta film over the cyan square.
17. Place at least 2 layers of magenta film over the magenta square.
18. Place at least 2 layers of magenta film over the yellow square.
19. Place at least 2 layers of yellow film over the red square.
20. Place at least 2 layers of yellow film over the green square.
21. Place at least 2 layers of yellow film over the blue square.
22. Place at least 2 layers of yellow film over the cyan square.
23. Place at least 2 layers of yellow film over the magenta square.
24. Place at least 2 layers of yellow film over the yellow square.

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<u>Assessment:</u>

1. Consider a cyan-colored piece of paper and a cyan-colored transparency film. Draw a diagram for each of these materials that explains why these objects are that color.
2. Using a diagram, explain why water appears blue.
3. Using a diagram explain why smog appears reddish.
4. Using a diagram, explain why plants appear green.
5. Consider how you feel when you wear a white shirt on a hot day compared to a dark shirt on a hot day. Why do you think this happens?
6. Using your explanation from item 5, what color shirt will keep you cooler on a hot day: red or magenta? Explain your reasoning.
7. You are in charge of stage lighting at a play and have only 1 spotlight that you can use. You can choose from blue, cyan, green, magenta, red, and yellow spotlights. During the course of the play, you want to make a yellow banana appear to be red. When the overhead (white) lights are turned off, what color spotlight should you shine on the banana? (Hint: Two different ones will work.) Explain your reasoning.
8. Explain why blood appears red - what colors does it absorb?
9. Explain why gold and copper appear yellowish in color.

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Experiment 3:
Overlapping Cyan, Magenta, Yellow, and Their Complementary Colors
(Student Activity Worksheet)

Materials Needed:

1. White paper
2. Cyan, magenta, and yellow films (1 set per group of 2-4)
3. Red, green, and blue films (1 set per group of 2-4)

Procedure:

As a class

1. From blue, cyan, green, magenta, red, and yellow colored films, predict which three colored films will produce the widest variation of colors when overlapped on a white piece of paper.

In groups of 2-4

2. On the white paper, place the cyan film over the yellow film. What color do you see? Explain why using a diagram and a math equation.
3. On the white paper, place the cyan film over the magenta film. What color do you see? Explain why using a diagram and a math equation.
4. On the white paper, place the yellow film over the magenta film. What color do you see? Explain why using a diagram and a math equation.
5. Based on the results of 2, 3, and 4, construct a color wheel that provides an explanation of these results. How does this color wheel relate to the one that you developed in Experiment 1?

6. On the white paper, place the cyan film over the yellow film over the magenta film. What color do you see? Explain why using a diagram and a math equation.

7. On the white paper, place the cyan film over the red film. What color do you see? Explain why using a diagram and a math equation.
8. On the white paper, place the yellow film over the blue film. What color do you see? Explain why using a diagram and a math equation.
9. On the white paper, place the magenta film over the green film. What color do you see? Explain why using a diagram and a math equation.
10. What relationship can you find that relates the results you obtained in 7, 8, and 9 to the color wheel you developed in 5.
11. Summarize the results above using a table.

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12. On the white paper, place the red film over the yellow film. What color do you see? Explain why.

13. On the white paper, place the red film over the blue film. What color do you see? Explain why.

14. On the white paper, place the yellow film over the blue film. What color do you see? Explain why.

As a class

15. What colors can be obtained by

a. Overlapping 2 colors at a time using red, yellow, and blue?

b. Overlapping 2 colors at a time using cyan, magenta, and yellow?

c. Overlapping 2 colors at a time using red, green, and blue?

Which set of colors would be the best colors to use to generate additional colors and why?

Primary colors produce the widest range of colors when mixed . Which are the 3 primary colors of colored films?

Assessment:

1. Complementary colors are 2 colors that when combined as light produce white and when combined as pigments - films, inks, or paints- produce black. (Artists often use complementary colors because they are stimulating to the eye.) Using diagrams and/or math, demonstrate the complementary colors of light and the complementary colors of pigments. What is the relationship between the complementary colors of light and the complementary colors of pigments.

2. a. Can cyan, magenta, or yellow be produced by overlapping other colors of films? If so, demonstrate this using a diagram.

b. Can red, green, or blue be produced by overlapping other colors of films? If so, demonstrate this using a diagram.

3. Mixing other colors also cannot make primary colors. What are the primary colors of light? What are the primary colors of pigment?

4. Prepare, by coloring or using colored paper, a circle or square that is one of the following colors: red, green, blue, cyan, magenta, or yellow. Stare at the color for 30 seconds. Now look at a white piece of paper. What do you see (the afterimage)? What is the color that you see? What is the relationship between the original color and the color of the afterimage? Propose a theory of how the eye works to explain this phenomenon.

5. a. Determine the resultant color when two dots of cyan and magenta are on top of one another and the adjacent dot area is white vs. when a magenta dot is adjacent to a cyan dot.

b. Determine the resultant color when two dots of red and blue are on top of one another and the adjacent dot area is white vs. when a red dot is adjacent to blue dot.

c. Discuss the implications of parts a and b for printing colors.

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6. (Advanced) Observe the color that occurs when a yellow film is placed on top of a magenta film and compare that to the color that occurs when a magenta film is placed on top of a magenta film. The model that we have been using is a simplification of the real world. In reality, a small percentage of the light is reflected at the top surface of a film. Using this fact, explain why a yellow film placed on top of a magenta film appears to be a different color than a magenta film on top of a yellow film.
(Hint: utilize the color wheel and recall that equal amounts of red, green, and blue light combine to make white light.)

7. (Advanced) Show how placing a bluish colored film top of a yellowish colored film can produce a green color. This will help you to understand why most people think that adding yellow and blue colors produce green, as shown in the traditional artist's color wheel.
(Hint: utilize the RGB color model on the computer and remember that no real colors are perfect.)

8. (Advanced) Show how placing a bluish colored film top of a reddish colored film can produce a purple color. This will help you to understand why most people think that adding red and blue colors produce purple, as shown in the traditional artist's color wheel.
(Hint: utilize the RGB color model on the computer and remember that no real colors are perfect.)

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Experiment 4:
Overlapping Gradients of Cyan, Magenta, Yellow, and Black
(Student Activity Worksheet)

Materials Needed:

1. White paper
2. Cyan (C), magenta (M), yellow (Y), and black (K) gradient transparency strips.

(Note: You couldn't use the letter B to represent black because that is already taken by the color blue. So you use the last letter of black - K)

3. Red (R), green (G), and blue (B) gradient transparency strips.

Procedure:

As a class

1. Predict and discuss how colors other than red, green and blue (for example, brown or orange or gray) could be made by overlapping cyan, magenta, and yellow films. What might be the technological implications of this?

In groups of 2-4

2. Find 5 objects with different colors.
3. By overlapping the CMYK gradient transparency rectangles, try to match the colors of the different objects. Try also to match the same colors using the RGB and K transparency rectangles.
4. Describe how much C, M, Y, and K were used to generate the color of the object.
5. Write a math expression that defines the color of each object in terms of CMYK.

As a class

6. Discuss how printers might use the four CMYK colors in their work. Discuss whether you could match the colors using RGBK.

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Assessment:

1. Develop an x-y graph, where x is the amount of cyan and y is the amount of magenta, that is a model for how cyan and magenta pigments mix. Label your axes and plot at least 6 data points. Label the coordinates of the data and describe their color. What are the limitations of this model?

2. Develop an x-y graph, where x is the amount of magenta and y is the amount of yellow, that is a model for how magenta and yellow pigments mix. Label your axes and plot at least 6 data points. Label the coordinates of the data and describe their color. What are the limitations of this model?

3. Develop an x-y graph, where x is the amount of yellow and y is the amount of cyan, that is a model for how yellow and cyan pigments mix. Label your axes and plot at least 6 data points. Label the coordinates of the data and describe their color. What are the limitations of this model?

4. Develop a color cube that represents the colors that can be made by mixing cyan. magenta, and yellow pigments.

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Experiment 5:
Color Printing using CMY
(Student Activity Worksheet)

Materials Needed:

1. 30 X illuminated hand held microscope (1 per group of 2-4)
2. Printed colored pages from magazines, comics, cereal boxes, newspapers, etc.
3. Cyan (C), magenta (M), yellow (Y), and black (K) gradient transparency strips.

Procedure:

As a class

1. Predict how color pages are printed.

In groups of 2-4

2. Using the handheld microscope, observe which dots produce different colors in the printed colored pages. Then try to match the color that you see (without the microscope) using the C, M, Y, K gradient transparency strips.

{Recall that in experiment 4, you learned that red is made by overlapping yellow and magenta dots, green is made by overlapping cyan and yellow dots, and blue is made by overlapping magenta and cyan dots. So translate the red, green, and blue dots that you see to cyan, magenta, and yellow. (It can be difficult to see the cyan, magenta, and yellow dots, particularly if you are looking at red, green, or blue regions, since the printers do a really good job of overlapping the CMY colors to make the RGB colors. Try looking at regions where there is significant color change to more easily see how differing percentages of cyan, magenta, yellow, and black are used to generate colors.)}

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3. Tabulate your data in the following way:

By eye	In micro-scope	In micro-scope	In micro-scope	In micro-scope	Visually-CMYK	Visually CMYK	Visually CMYK	Visually CMYK
Color observed	% area covered by cyan dots	% area covered by magenta dots	% area covered by yellow dots	% area covered by black dots	% C (using gradient strip)	% M (using gradient strip)	% Y (using gradient strip)	%K (using gradient strip)

4. What conclusions can you make concerning how printed colors are made?

5. What inks are used in a color ink jet printer and why?

<u>As a class</u>

6. Discuss how color printing works. Using these ideas, discuss how color photography might work.

<u>Assessment:</u>

1. Using cyan, magenta, and yellow dots printed on top of one another, show how printing makes the following colors:

a. black
b. red
c. green
d. blue
e. cyan
f. magenta
g. yellow
h. white
i. gray
j. orange.

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Experiment 6:
Mixing RGB or CMY Colors with the Color Wheel
(Student Activity Worksheet)

Materials Needed:

1. Large diameter and small diameter transparent color wheel.
2. R, G, B, C, M and Y small diameter transparent color wheels.

(Work in groups of 2-4 and share the color wheels between groups.)

Procedure:

As a class

1. Predict what concepts you could demonstrate using a color wheel and different colored rings.

In groups of 2-4

2. On a white piece of paper, overlap the large diameter and small diameter color wheels so that yellow is on the top of the large diameter color wheel and yellow is on the bottom of the small diameter color wheel. Why are the overlapped areas all black (or at least very dark)?
3. In a similar way overlap the R color wheel with the large diameter color wheel. What colors do you see? Why?
4. In a similar way overlap the G color wheel with the large diameter color wheel. What colors do you see? Why?
5. In a similar way overlap the B color wheel with the large diameter color wheel. What colors do you see? Why?
6. In a similar way overlap the C color wheel with the large diameter color wheel. What colors do you see? Why?
7. In a similar way overlap the M color wheel with the large diameter color wheel. What colors do you see? Why?
8. In a similar way overlap the Y color wheel with the large diameter color wheel. What colors do you see? Why?

As a class

9. Discuss how artists use a few colors to produce many colors when they paint.

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Assessment:

1. Discuss why the color wheel used in this experiment is a better model than the traditional color wheel. (In the traditional color wheel, the primary colors are red, yellow, and blue; and the secondary colors are orange, green, and purple.)

2. Explain why red, yellow, and blue are not appropriate primary colors.

3. Discuss why the complementary colors in the traditional color wheel are incorrect.

4. Using the color wheel transparency and the cyan, magenta, and yellow transparency sheets:

a. Describe how you can demonstrate that white light is composed of red, green, and blue light.

b. Describe how you can demonstrate the rules for additive color mixing.

5. Blue plays no part in our perception of brightness, so that colors that differ only in the amount of blue don't produce sharp edges. Colors that differ only in the amount of blue are therefore difficult to differentiate, so they are poor choices for foreground/background colors in paintings, digital images, or overhead transparencies. Based on this information, what color combinations should be avoided?

6. Human visual perception can be thought of as a system of color sensors (hardware) followed by some color processing (software). Try to figure out how the hardware and software works given the following information:

1. Using red, green, and blue lights, we can produce all colors ((Hint: this relates to the hardware)
2. Color blind people are cannot differentiate either reds and greens or yellows and blues. (Hint: software)
3. We do not see reddish greens or yellowish blues.
4. Blue plays no part in our perception of lightness or brightness. (Hint: software)
5. Red light + green light produces the sensation of yellow light. (Hint: software)
6. In the L* a* b* color system, which is based on the human visual system, the positive x-axis refers to redness, the negative x-axis refers to greenness, the positive y-axis refers to yellowness, the negative y-axis refers to blueness, and z axis represents lightness or brightness - from black to white.(Hint: software)

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7. Make up a song, rap or poem about color.

8. (Advanced) Investigate the CIE Chromaticity diagram or L*a*b* color space. Give an oral report to the class about it. Compare and contrast these models to the color wheel. Use the references provided at the end of this unit.

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Teacher's Guide

Experiment 1: Light Emitting Colors and Their Color Mixing

Purpose:

To investigate how additive color mixing works using a color monitor.

Discussion:

Benchmark 4F 8th grade: "Something can be 'seen' when light waves emitted or reflected by it enter the eye-just as something can be 'heard' when sound waves from it enter the ear."
Benchmark 4F 8th grade: "Human eyes respond to only a narrow range of wavelengths of electromagnetic radiation-visible light Differences of wavelength within that range are perceived as differences in color."

Our eyes are sensitive to three primary colors, red, green and blue. That is because our eyes contain three different types of color receivers called cones. As shown in Fig. 1, we each have long wavelength sensitive cones for seeing mostly red light; middle wavelength sensitive cones for seeing mostly green light and short wavelength sensitive cones for seeing mostly blue light. Our brain interprets different amounts of red, green and blue light that hits our eyes at once as various colors. (See also Figure 2 for some additional details.) If only red light hits our eye, we see the object as red. If equal amounts of red light and green light hit our eyes, we see yellow. If no light hits our eyes, we see black and if equal amounts of red, green and blue light hit our eyes, then we see white. These and other combinations are shown in Table 1 below. Note that red, green and blue are called the primary colors of light or the primary additive colors because adding them in different combinations produces most of the colors that we can see.

Recall that the order of colors in a rainbow (decreasing wavelength) is Red-Orange-Yellow-Green-Blue-Indigo-Violet (ROY G. BIV). Our brain averages the colors that strike our eye according to the order of colors in the rainbow. This is why when both red and green light strike our eye, we see yellow (yellow is in between red and green in the rainbow).

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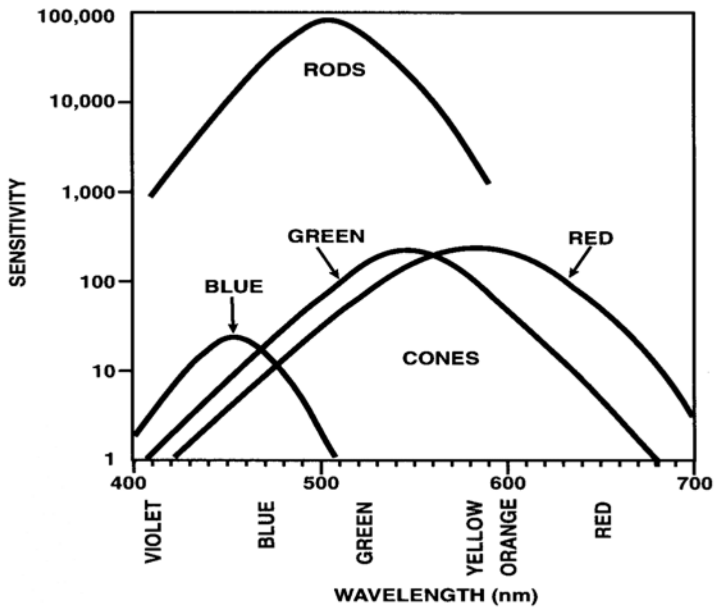

Figure 1. The sensitivity of the rods and cones of the human eye in arbitrary units as a function of wavelength of light. The rods in our eyes are very sensitive to light and enable us to see at night while the three types of cones give us color vision during the day. The sensitivity of the short wavelength "blue" cones, middle wavelength "green" cones, and long wavelength "red" cones are shown. The colors labeled on the x-axis indicate how our eye interprets the particular wavelengths shown as colors.

Relationship of Color to Electromagnetic Spectrum

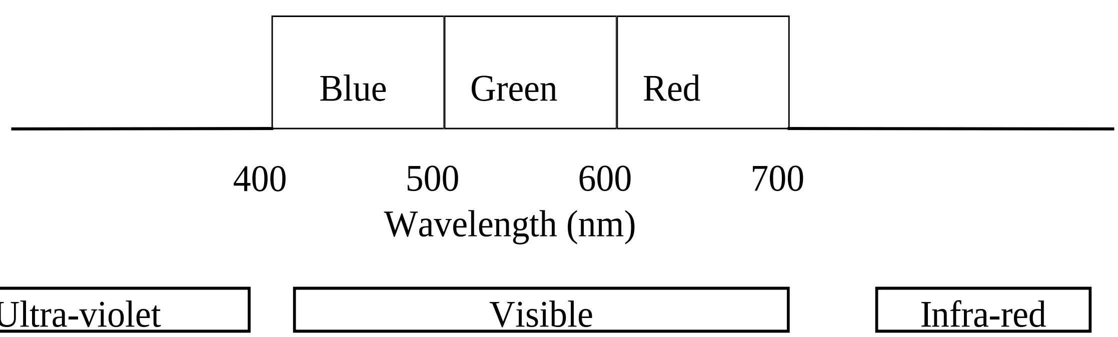

Fig. 2. Color and the electromagnetic spectrum. Note that we may perceive the same color, even if different wavelengths of light enter our eye. For example, we see a color as red if light of the single wavelength of 650 nm enters our eye. We also see red if a band of light consisting of all wavelengths between about 600 and 700 nm enters our eye.

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Table 1: When equal intensities of light of the colors in the first 3 columns strikes your eye, you see the color in the 4th column

RED	GREEN	BLUE	You see
			BLACK
X			RED
	X		GREEN
		X	BLUE
X	X		YELLOW
	X	X	CYAN
X		X	MAGENTA
X	X	X	WHITE

Benchmark 9B 5th grade: "Tables and graphs can show how values of one quantity are related to values of another."
Benchmark 9B 12th grade: "Tables, graphs, and symbols are alternative ways of representing data and relationships that can be translated from one to another."
Benchmark 11B 12th grade: "The basic idea of mathematical modeling is to find a mathematical relationship that behaves in the same ways as the object or processes under investigation. A mathematical model may give insight about how something really works or may fit observations very well without any intuitive meaning."

This table can be restated in a simple mathematical form using color addition and color subtraction, as shown below. In this way, students can be shown that colors can be added and subtracted in the same way as numbers. In addition, color algebra can be performed, as demonstrated below.

<u>Color Addition</u>

Red + Green = Yellow
Green + Blue = Cyan
Red + Blue = Magenta
Red + Green + Blue = White

Complementary Colors (of Light)

Red + Cyan = Red + Green + Blue = White
Green + Magenta = Green + Red + Blue = White
Blue + Yellow = Blue + Red + Green = White

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Color Subtraction

White - Red = Green + Blue = Cyan
White - Green = Red + Blue = Magenta
White - Blue = Red + Green = Yellow
White - Red - Green = White - (Red + Green) = White - Yellow = Blue
White - Red - Blue = White - (Red + Blue) = White - Magenta = Green
White - Green - Blue = White - (Green + Blue) = White - Cyan = Red

Complementary Colors (of Paint or Ink)

White - Red - Cyan = White - Red - Green - Blue
= White - (Red + Green + Blue) = White - White = Black
White - Green - Magenta = White - Green - Red - Blue
= White - (Red + Green + Blue) = White - White = Black
White - Blue - Yellow = White - Blue - Red - Green
= White - (Red + Green + Blue) = White - White = Black

Some examples of color algebra are shown below:

Color Algebra

Red + x = Yellow
x = Yellow - Red = (Red + Green) - Red = Green
Green + x = Cyan
x = Cyan - Green = (Blue + Green) - Green = Blue
Blue + x = Magenta
x = Magenta - Blue = (Red + Blue) - Blue = Red
White - x = Blue
x = White - Blue = (Red + Green + Blue) - Blue
= Red + Green = Yellow
White - x = Green
x = White - Green = (Red + Green + Blue) - Green
= Red + Blue = Magenta
White - x = Red
x = White – Red = (Red + Green + Blue) - Red
= Green + Blue = Cyan
White - x = Cyan
x = White - Cyan = (Red + Green + Blue) - (Green + Blue)
= Red
White - x = Magenta
x = White - Magenta = (Red + Green + Blue) - (Red + Blue)
= Green
White - x = Yellow
x = White - Yellow = (Red + Green + Blue) - (Red + Green)
= Blue
White - x = White

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x = White - White = Black (No colors)
White - x = Black
x = White - Black = White

We will later show how solutions to these addition, subtraction, and algebra problems can be determined using additive and subtractive color mixing experiments.

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When this light strikes your eyes	You see this color
No light	Black
Red	Red
Green	Green
Blue	Blue
Red Green	Yellow
Green Blue	Cyan
Red Blue	Magenta
Red Green Blue	White

What about other colors that we commonly encounter, such as orange or purple? The other colors are seen when non-equal amounts of red, green or blue light hits our eye. In this case, our eye sees the colors in between. For example, we see orange when only red and green light hits our eye, but there is more red than green. This can be seen from table 1 above, since we know that orange is between red and yellow. Adding red (one part red) to yellow (one part red and one part green) results in orange (two parts red and one part green). Similarly, since purple is between magenta (one part red and one part blue) and blue (one part blue), we see purple when both red and blue light strikes our eye but there is more blue than red.

Note that the rainbow extends from the long wavelength visible color, red, to the short wavelength visible color violet. Colors from violet to red on the color wheel, such as magenta, are not part of the rainbow: these violet to red colors can be formed by mixing different amounts of red and blue light.

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<u>Advanced aside: What is at the (Short Wavelength) End of the Rainbow?</u>

There may be some confusion about what colors are actually seen in the rainbow at the short wavelength end and why. (This topic confused me until quite recently.) Some pictures and charts from respectable sources may either show blue, violet, or magenta as the color at the short wavelength end of the rainbow. What colors are seen?

As can be verified by looking at a rainbow, through a prism or diffraction grating, or at the color of a short wavelength laser, we see violet as the color corresponding to the shortest wavelength visible to us. Yet, this seems to be in contradiction to two facts presented earlier:

1. The shortest wavelength cone (which allows us to see blue colors) is essentially the only cone stimulated at short wavelengths.
2. Violet is the result of both short wavelength and long wavelength light striking our eye.

This seems to be a major problem. We see a color that involves both long wavelength light (red) and short wavelength light (blue) when only short wavelength light enters our eye!

That the perception of red re-emerges at short wavelengths is inconsistent with our previous model of human color vision - that of 3 cones which produce the sensation of red, green, and blue colors – or mixtures, corresponding to the incoming wavelengths. The answer, still apparently not totally understood, apparently lies in how the signals from the cones are interpreted by the brain. Somehow, light with wavelength near 400 nm, which only stimulates the blue (short wavelength) cone, also stimulates the sensation of red somewhere in the processing of this signal after it has been sensed by the short wavelength sensitive cone. This interpretation is in accord with the so-called "opponent color model" of human color vision. Note that this is a simple experiment that demonstrates the complexity of human color vision.

That the violet color is often incorrectly shown on spectrum charts generally is a result of the limitations of the color printing process. It is difficult to reproduce the color violet using standard 4 color (CMYK) printing - it is also difficult (actually impossible) to reproduce all of the colors that we can see using just 4 color printing. However, magenta should never be shown on a chart of the visible spectrum because it is not a color that is observed in a rainbow or prism - magenta is a "non-spectral" color. It is a result of mixing “equal” amounts of red and blue light. (Note that we perceive violet light as blue light mixed with a relatively small amount of red light.)

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Teacher's Guide to Procedure:

Benchmark 1B 2nd grade: "Tools such as thermometers, magnifiers, rulers, or balances often give more information about things than can be obtained by just observing things without their help."
Benchmark 12D 8th grade: "Students should be able to organize information in simple tables and graphs and identify relationships they reveal."

1. a Write down student predictions.
b. They will probably remember the (incorrect) traditional color wheel where the primary colors are red, yellow, and blue; and the secondary colors are orange, green, and purple. This (incorrect) color wheel shows what happens when you mix colors of paint. As they will discover, the correct color wheel models both light and paint (and ink and pigments).

2. Perform as written.

3. Use a 8x magnifier, such as the one that is part of the Radio Shack handheld microscope.

4. This activity demonstrates that there are many ways to model experiments.

a. Colors:

RED	***GREEN***	***BLUE***	***You see***
			BLACK
X			RED
	X		GREEN
		X	BLUE
X	X		YELLOW
	X	X	CYAN
X		X	MAGENTA
X	X	X	WHITE

Gray Scales:

RED	***GREEN***	***BLUE***	***You see***
			BLACK
Dim	Dim	Dim	Dark Gray
Brighter than dark gray	Brighter than dark gray	Brighter than dark gray	Gray
Brighter than gray	Brighter than gray	Brighter than gray	Light Gray
Max	Max	Max	WHITE

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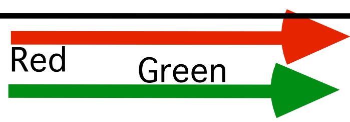
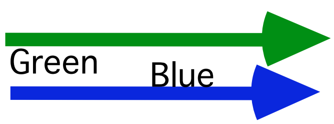
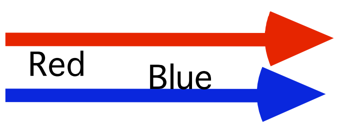
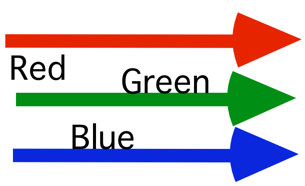
Note that the colors of red, green, and blue seen using the magnifier may look different that the large squares of colors on the monitor seen without the magnifier. This indicates the complexity of human color vision: the human perception of color can change depending on the surrounding colors and the field of view.

4. b.

<u>Color Addition</u>

Red + Green + Blue = White
Red + Green = Yellow
Green + Blue = Cyan
Blue + Red = Magenta

c.

When this light strikes your eyes	You see this color
	Yellow
	Cyan
	Magenta
	White

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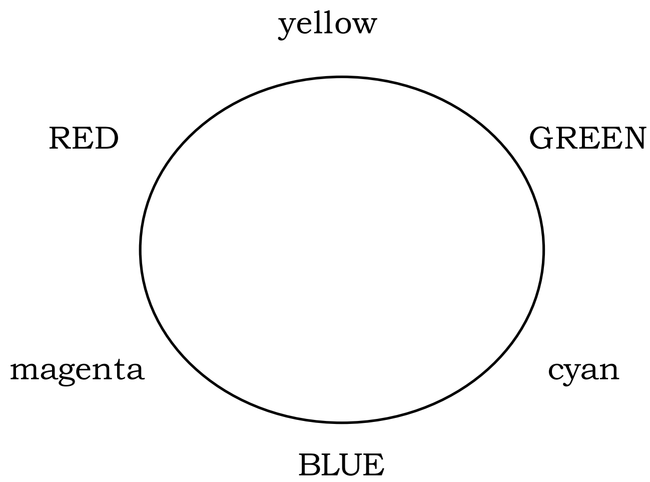
5.



6. a. As stated.

b. Orange is a mixture of red and green, with the red being more intense than the green. This could be predicted using the color wheel. Light green is mostly green, with the green bright, and with the red and blue also on.
Dark green is mostly a dim green, with the red and blue off or barely on. Note that our color wheel does not model dark and light colors. It is an appropriate model for the hue, but not for the brightness or darkness of a color. Point out that models are useful, but also have limitations.

7. Stress to your students that the computer monitor screen produces these colors, i.e. it is the source of the color. The color does not rely on reflected room light or sunlight. To prove this, turn off the lights in the classroom so that it is dark and have them note that the colors seen do not change.

You should point out to your students that a TV screen also produces these colors, i.e. it is the source of the color. The color does not rely on reflected room light or sunlight. To prove this, turn off the lights in the TV room so that it is dark and have them note that the colors on the TV do not change. The same three colors are used in the TV set and the color monitor, namely red, green and blue. Motion is produced by sequentially making the colors light or dark. The computer monitor uses red, green and blue dots whereas the TV uses red, green and blue rectangles or stripes. Have your students look at a TV and write a description of how colors are made on a TV set and how they are alike as well as how they are different from the way colors are made on a computer monitor.

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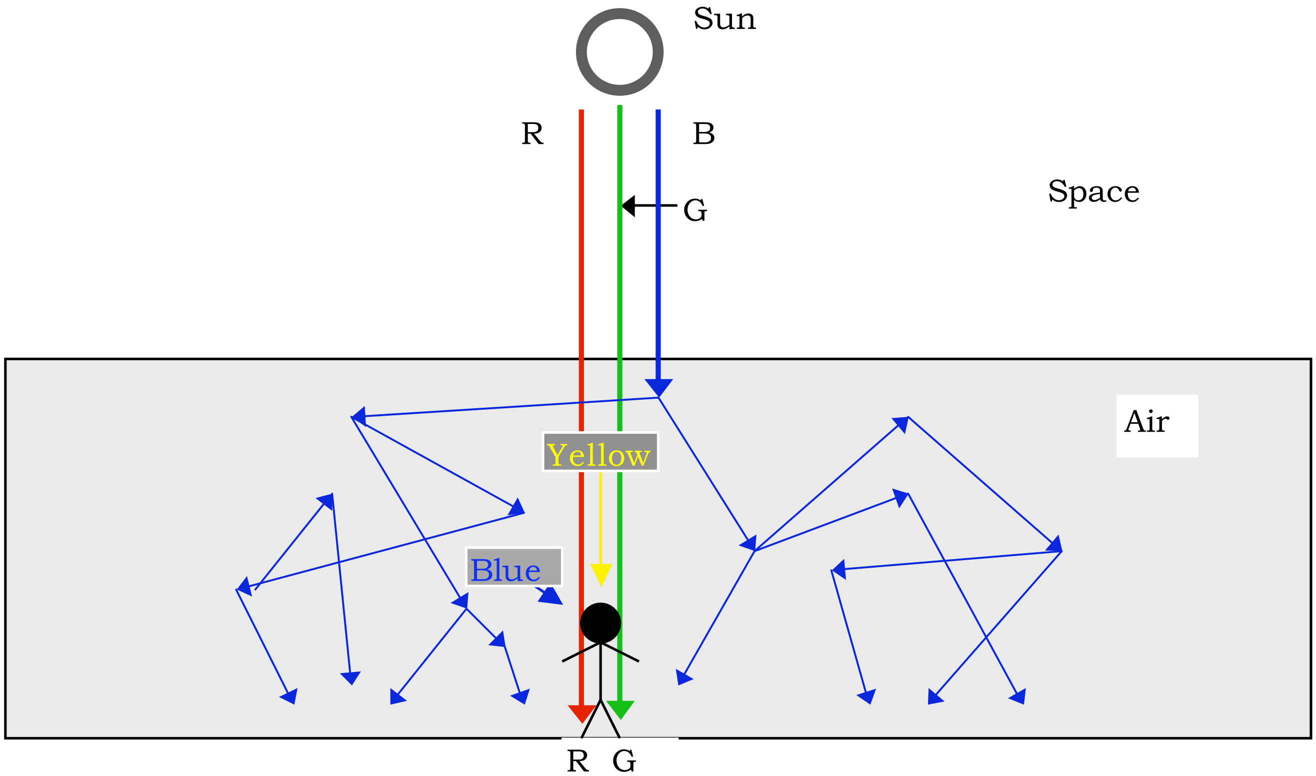
Assessments

1. The sun appears to be yellow (red+green), since the blue component was scattered. If you look away from the sun, the gas (air) appears to be blue, since the scattered blue light is all that enters your eye from those parts of the sky. (This is an oversimplification. See the "Colors of the Sky" article in the references for a more complete explanation,)



Note that the blue sky and the yellow sun are a memorable combination of complementary colors. The initially white light of the sun is separated by the atmospheric scattering into the complementary colors of yellow (sun) and blue (sky).

(Additional Details: This effect is called Rayleigh scattering. Lord Rayleigh showed that the amount of light scattered is inversely proportional to the fourth power of wavelength for sufficiently small particles. Thus, blue light is scattered more than red light by a factor of 10, since $(700\text{nm}/400\text{nm})^4=10$. The small particles are that cause the scattering are air molecules: oxygen and nitrogen.)

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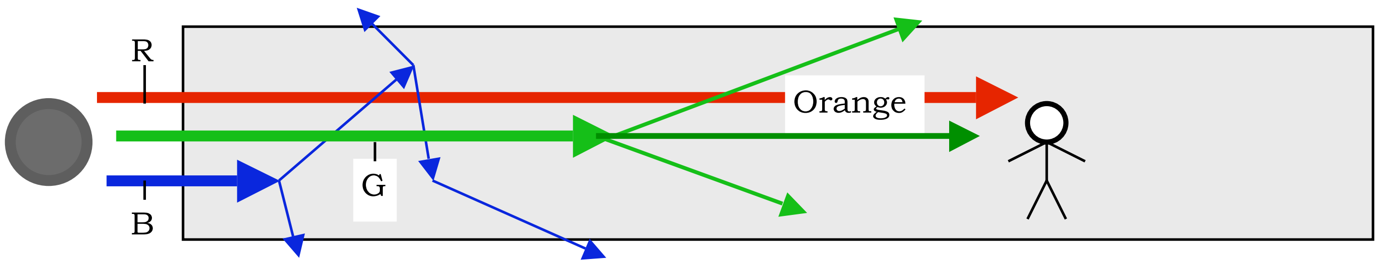
2. The type of diagram used above can also be used to explain the color theory behind the orange/red sunsets. When the sun is overhead, the sun light passes through a small amount of air, which tends to scatter the blue light. When the sun is near the horizon, the sun light must pass through a thicker layer of air, which tends to scatter the blue light strongly, the green light less strongly, and the red light hardly at all. Since most of the red, just some of the green and almost none of the blue light reaches your eye, the sun appears red or orange when the sun sets.



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3. a. black
   b. red
   c. yellow (red + green = yellow)
   d. white (red + green + blue = white)
   e. cyan (green + blue = cyan)
   f. blue
   g. black

As objects heat up, their color changes from black to red to yellow to white to cyan to blue to black.

The hottest visible part of an object is the blue part. As the temperature of an object or flame increases, the color changes from red to yellow to white to cyan to blue. The simplified color model used in this module can be used to demonstrate this. For a more accurate and detailed description, look for references on blackbody radiation.

Let's suppose that an object gives off white light. That light can be modeled as equal amounts of red, green and blue light.

Benchmark 4A 12th grade: "The stars differ from each other in size, temperature and age, but they appear to be made up of the same elements that are found on the earth and to behave according to the same physical principles. Unlike the sun, most stars are in systems of two or more stars orbiting around each other."

Now suppose that the temperature of the object or flame decreases. The spectrum of light given off shifts towards the red end of the spectrum. The part that was red shifts into the infra-red, which is invisible to the eye. The part that was green shifts to red and the part that was blue shifts to green. Therefore your eye sees the additive mixture of red and green light, which your eye interprets as yellow light.

Now suppose that the temperature of the object or flame decreases further. The spectrum of light given off shifts even further towards the red end of the spectrum. The part that was in the infra-red shifts further into the infra-red, which is invisible to the eye. The part that was red shifts into the infra-red, which is invisible to the eye. The part that was green shifts to red. Therefore your eye sees just red.

Now suppose that the temperature of the object or flame decreases further. The spectrum of light given off shifts even further towards the red end of the spectrum. The parts that were in the infra-red shift further into the infra-red, which is invisible to the eye. The part that was red shifts into the infra-red, which is invisible to the eye. Therefore, no visible light reaches your eye, so the object appears black.

Now suppose that the original object or flame temperature increases. The spectrum of light given off now shifts towards the blue end of the spectrum. The part that was red shifts to green. The part that was green shifts to blue. The part that was blue shifts into the ultra-violet, which is invisible to your eye. Therefore your eye sees the additive mixture of green and blue light, which your eye interprets as cyan light.

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Now suppose that the temperature of the object or flame increases further. The spectrum of light given off shifts even further towards the blue end of the spectrum. The part that was green shifts to blue. The part that was blue shifts into the ultra-violet, which is invisible to your eye. The part that was in the ultra-violet shifts further into the ultra-violet, which is invisible to your eye. Therefore your eye sees just blue.

Now suppose that the temperature of the object or flame increases further. The spectrum of light given off shifts even further towards the blue end of the spectrum. The part that blue shifts into the ultra-violet, which is invisible to your eye. The parts that were in the ultra-violet shift further into the ultra-violet, which are invisible to your eye. Therefore your eye sees the object as black.

These concepts are shown schematically on the next page.

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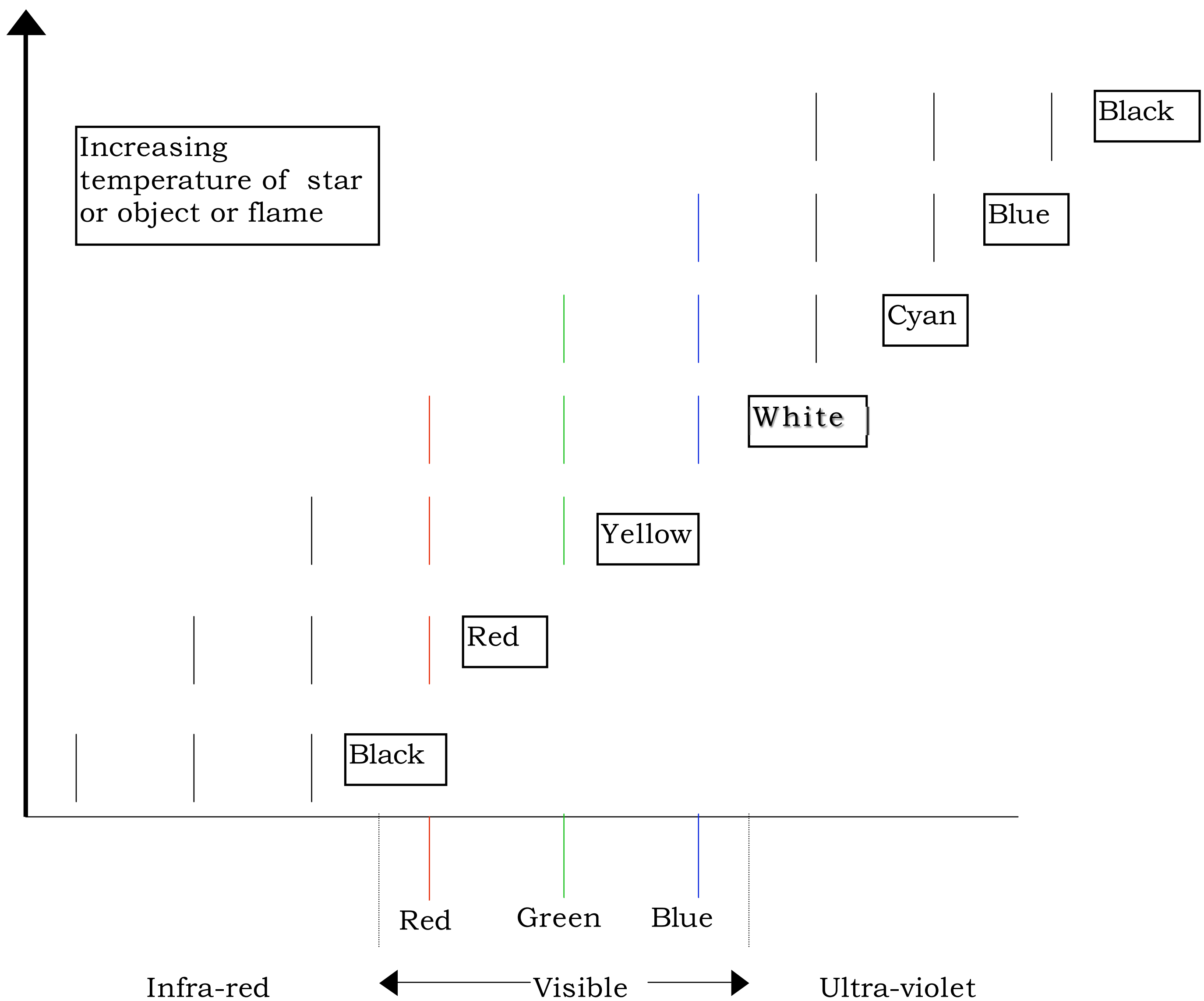
How Color Changes with Increasing Temperature



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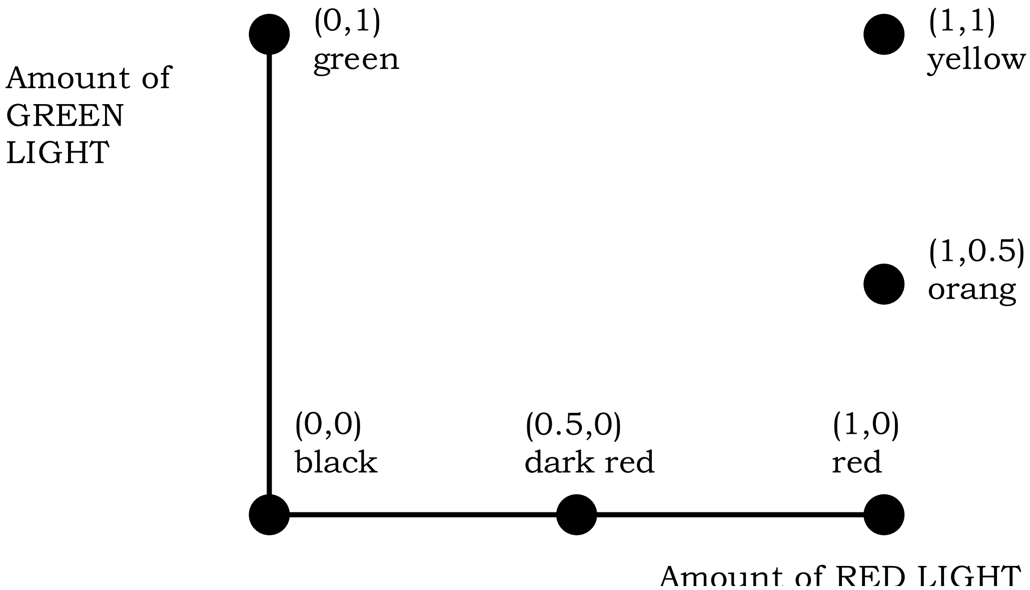
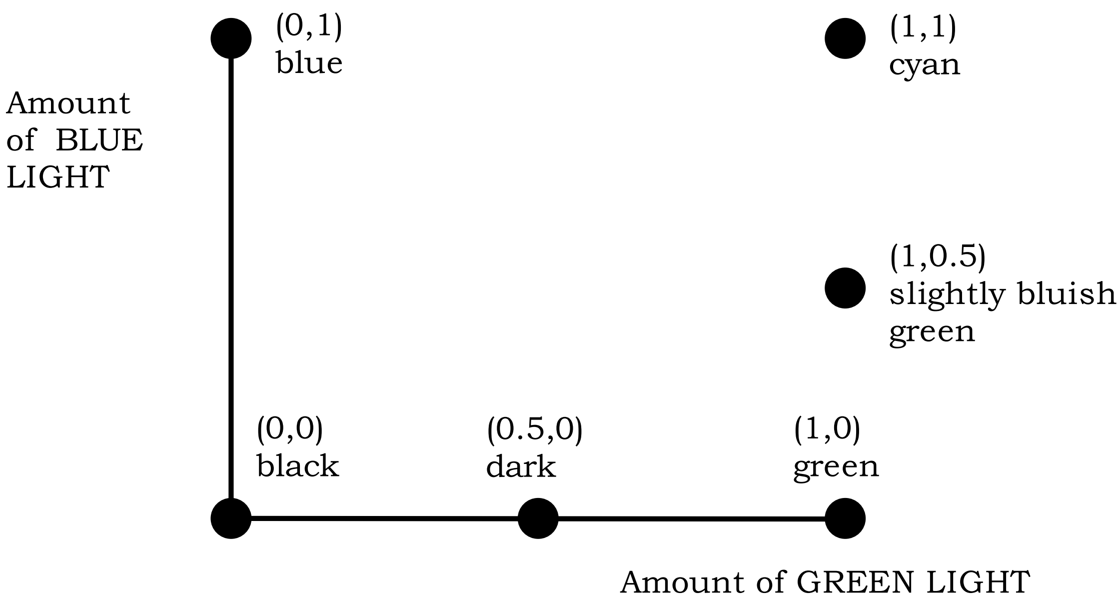
4. This model does not include colors that contain blue light.



5. This model does not include colors that contain red light.



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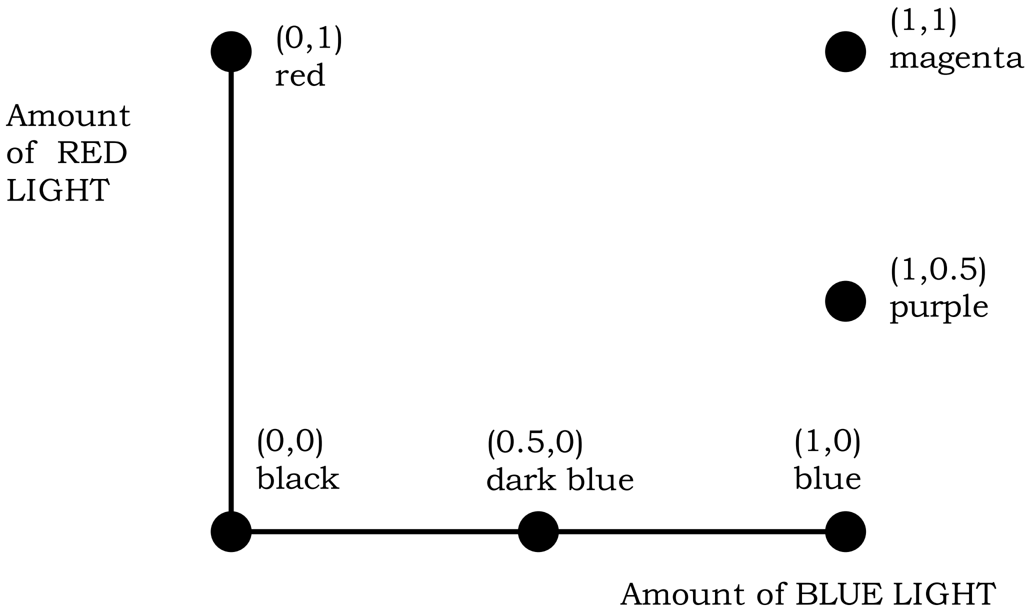
6. This model does not include colors that contain green light.



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7. RGB Color Cube

Benchmark 11B 8th grade: "Different models can be used to represent the same thing What kind of model to use and how complex it should be depends on its purpose. The usefulness of a model may be limited if it is too simple or if it is needlessly complicated. Choosing a useful model is one of the instances in which intuition and creativity come into play in science, mathematics, and engineering."
Benchmark 11B 12th grade: "The usefulness of a model can be tested by comparing its predictions to actual observations in the real world. But a close match does not necessarily mean that the model is the only 'true' model or the only one that would work."
Benchmark 12D 8th grade: "Students should be able to read simple tables and graphs produced by others and describe in words what they show."
Benchmark 12D 8th grade: "Students should be able to find and describe locations on maps with rectangular and polar coordinates."

Another way to describe colors is to use the a 3-dimensional coordinate system, the x, y and z axes , where the x-axis is the amount of red in the light, the y-axis is the amount of green in the light and the z-axis is the amount of blue in the light. In this model, we have the following colors:

(x,y,z) = (red, green, blue)
(0,0,0) = black
(1,1,1) = white
(1,0,0) = red
(0,1,0) = green
(0,0,1) = blue
(1,1,0) = yellow
(0,1,1) = cyan
(1,0,1) = magenta

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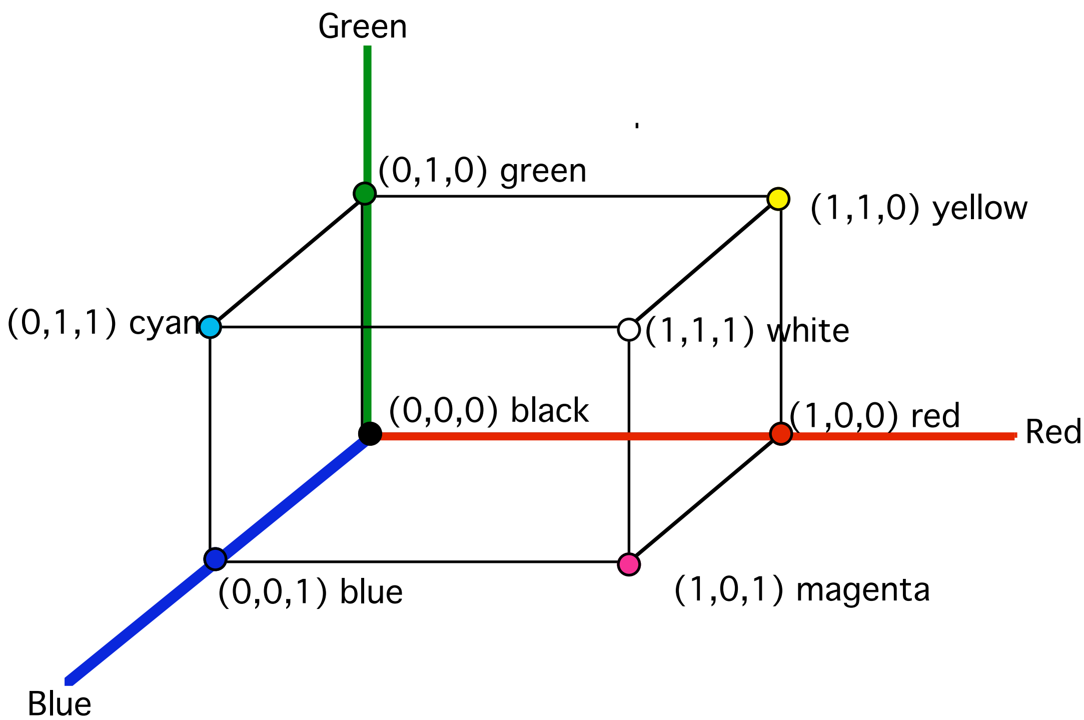
RGB COLOR CUBE



Note that for complementary colors, the sum of the coordinates is (1,1,1), the same as white light. These dimensions define a color cube for additive color mixing. The color wheel is obtained from the color cube by continuously traversing around the color cube subject to the following conditions:

- One of the coordinates always has a value of 1
- One of the coordinates always has a value of 0
- One of the coordinates always has a value that is greater than or equal to 0 and less than or equal to 1.

A color hexagon is a better mapping of the pure hues of the 3 dimensional color cube onto a 2-dimensional plane than is the round color wheel, although the color wheel is more commonly used, especially for artists. For the hexagon, the colors R, M, B, C, G, Y would consecutively lie at the vertices of the regular hexagon.

A three dimensional model of the color cube can be seen (and purchased) at the following address.
http://www.colorcube.com/

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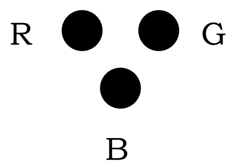
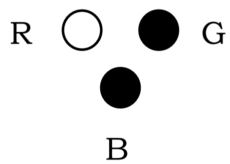
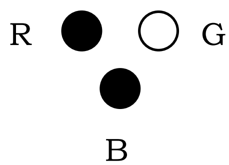
8.



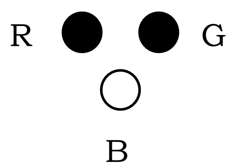
Black



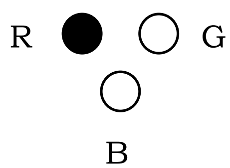
Red



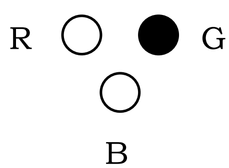
Green



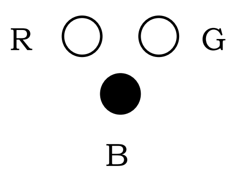
Blue



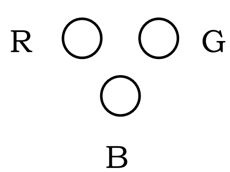
Cyan



Magenta

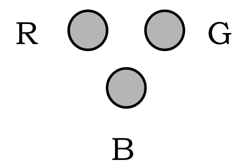


Yellow

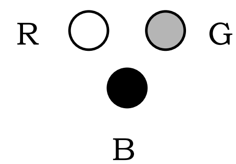


White

If the circle is black, it means the colored dot or pixel is not giving off any light, i.e., it is dark. If the circle is white, it is giving off the color of light denoted by the RGB label. If it is gray, it is giving off a reduced amount light.



Gray



Orange

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9a. Since it absorbs all colors, the semiconductor appears black.
9b. Since it absorbs green and blue light, it appear red.
9c. Since it absorbs blue light, it appears yellow, because its color results from the combination of the remaining red and green light.
9d. Since it doesn't absorb any color of light, it appears clear or white.

10a. If it doesn't emit any visible light, it appears black.
10b. The material emits red light, so it appears red.
10b. The material emits green light, so it appears green.
10b. The material emits blue light, so it appears blue.

11a. Since it absorbs red light only, it appears cyan, because its color results from the combination of the remaining green and blue light.
11b. Since it absorbs green light only, it appears magenta, because its color results from the combination of the remaining red and blue light.
11c. Since it absorbs blue light only, it appears yellow, because its color results from the combination of the remaining red and green light.

12a. The material emits red light, so it appears red.
12b. The material emits green light, so it appears green.
12c. The material emits blue light, so it appears blue.

13a. The sun would be white, since there is no atmosphere to scatter any of the sun's light.
13b. The sky would be black, since none of the sunlight would be scattered. (The pictures taken by the astronauts on the moon nicely verify this.)

14a. If the atmosphere is much denser, then all of the light from the sun will be scattered. So the color of the sun will be the same as the color of the sky, a grayish color. The sun will therefore appear to be much dimmer. This is similar to the situation on a cloudy, overcast day.
14b. The sky will be brighter, since more of the sun's light will be scattered. The sky will have much less blue color - it will be closer to light gray.

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Extra Activities

1. Alternate Procedure:

Using the Tabletop light mixer, examine and record the colors that you see when you turn on the following lights using the color-coded control dials.

1. Red
2. Green
3. Blue
4. Red + Green
5. Red + Blue
6. Green + Blue
7. Red + Green + Blue

Solution:

1. Red
2. Green
3. Blue
4. Yellow
5. Magenta
6. Cyan
7. White

Also note how large a range of colors can be generated using just these three colors by varying the dial settings.

Note that this experiment can be used in conjunction with color math to verify the solutions. Some examples are shown below.

Addition:

Red + Green = Yellow.

Turn on the red dial. Then turn on the green dial. Notice how the color changes to yellow.

Subtraction:

White - Red = Cyan

Turn on the red, green, and blue dials to make white light. Now subtract red light by turning the red light off. The resulting color is cyan.

Algebra:

Red + x = Yellow

Turn on the red light. Now determine what other light must be added to the red light to make yellow light. The answer is green light.

White - x = Cyan.

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Turn on the red, green, and blue dials to make white light. Now determine which light must be turned off (i.e. subtracted or removed) to make cyan light. The answer is the red light must be turned off.

2. Other ways to demonstrate color mixing

Demonstrate additive color mixing (or the RBG color model) using a color model program that might be available on your computer.

Example 1: Use the computer program Microsoft PowerPoint 4.0 for Macintosh (with MAC OS 8). Select the "Text Color" tool in the tool bar and select "Other Color." Then select "More Colors." Then select the RGB Picker. Using the red/green/blue (RGB) color model, verify the color mixing described in this Experiment.

Example 2:

Use the computer program ClarisWorks 4.0 for Macintosh (with MAC OS 8). Select Painting. In the Painting program, select and drag the Fill Color palette into the document area so it is permanently displayed. Then double click on any color square in the palette. Then select the RGB Picker. Using the red/green/blue (RGB) color model, verify the color mixing described in this Experiment.

Example 3: Download the following Java Applet from the World Wide Web:
http://mc2.cchem.berkeley.edu/Java/emission/emission.html
Use the red/green/blue color model to verify the color mixing described in this experiment.

Benchmark 11B 8th grade: "Mathematical models can be displayed on a computer and then modified to see what happens."

Benchmark 11B 12th grade: "Computers have greatly improved the power and use of mathematical models by performing computations that are very long, very complicated, or repetitive. Therefore computers can show the consequences of applying complex rules or of changing the rules. The graphic capabilities of computers make them useful in the design and testing of devices and structures and in the simulation of complicated processes

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3. Another Approach:

Set up 2 slide projectors. In front of each projector, place the following colors:

Projector 1	Projector 2	Resultant Color
Red	Green	Yellow
Green	Blue	Cyan
Blue	Red	Magenta
Red	Cyan	White
Green	Magenta	White
Blue	Yellow	White

Have your students predict the color that will result. Have them draw a color wheel that represents the result of the first 3 mixtures. Using color math, have the students predict the last 3 results based on the first three.

4. Another Approach:
See assessment 4 of experiment 6 for another way to present this.

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Teacher's Guide
Experiment 2: Colors That Absorb Light

Purpose:

To investigate the subtractive or absorptive properties of transparent films of different colors.

Discussion: How we see colored objects:

Recall again that the colors that we see depend on the relative amounts of red, green or blue light that shines on our eyes, as summarized in Table 1. Consider the three colors cyan, yellow and magenta. Each of them consists of a combination of two of the primary colors of light.

Let us consider in detail the color yellow. An object appears to be yellow if light coming from the object consists of an equal mixture of red and green light without any component of blue light. For a light source such as a computer monitor, yellow light was produced using red and green light.

Now let's consider how an object such as a banana looks yellow. The banana is certainly not a source of light. We observe that it has color only when room light or sunlight illuminates it. Room light or sunlight is white light in that it is a mixture of all the colors, including red, green and blue light. We know this because we have seen how water or glass or a prism can produce a rainbow from sunlight or room light. The banana has color because it is illuminated by white light and some of that light is reflected by the banana back to our eyes.

Benchmark 4F 8th grade: "Light from the sun is made up of a mixture of many different colors of light, even though to the eye the light looks almost white. Other things that give off or reflect light have a different mix of colors."

What part of the white light has been reflected back to our eyes for us to see that the banana is yellow? The banana must have reflected equal amounts of the red and green portion of the white light back to our eye and it must not have reflected any of the blue light back to our eye. In other words, it absorbed all of the blue light. Therefore yellow can be viewed as the color which absorbs all of the blue part of the white light and does not absorb any of the red or green part of the white light. In other words, yellow subtracts or removes blue light from white light. Yellow is called one of the primary subtractive colors.

In a similar manner, from Table 1, it can be seen that cyan is the color which absorbs (subtracts) red light and magenta is the color which absorbs (subtracts) green light. Cyan, yellow and magenta are called the primary subtractive colors. These results are summarized in the table below

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Now let's consider objects that appear to be one of the primary colors, such as a red apple. Again, the apple does not give off light, so that its color must be due to light that is reflected off of it. For the apple to appear to our eyes to be red, only red light must be reflected off of the apple, so that only red light strikes our eyes. Therefore, the red apple must absorb all light other than red. In other words, it absorbs the green and the blue parts of the white light.

Thus, a red object absorbs all light other than red so that it reflects only red light back to our eyes. Similarly, a blue object absorbs all light other than blue and reflects only blue light back to our eyes. Finally, a green object absorbs all light other than green and reflects only green light back to our eyes.

The absorptive or subtractive properties of colors are shown in Table 2 below.

Table 2: How we see colored objects

When white light strikes a surface with the color	These colors are absorbed			So these colors are reflected			So you see
	RED	GREEN	BLUE	RED	GREEN	BLUE	
WHITE				X	X	X	WHITE
CYAN	X				X	X	CYAN
YELLOW			X	X	X		YELLOW
MAGENTA		X		X		X	MAGENTA
RED		X	X	X			RED
GREEN	X		X		X		GREEN
BLUE	X	X				X	BLUE
BLACK	X	X	X				**BLACK**

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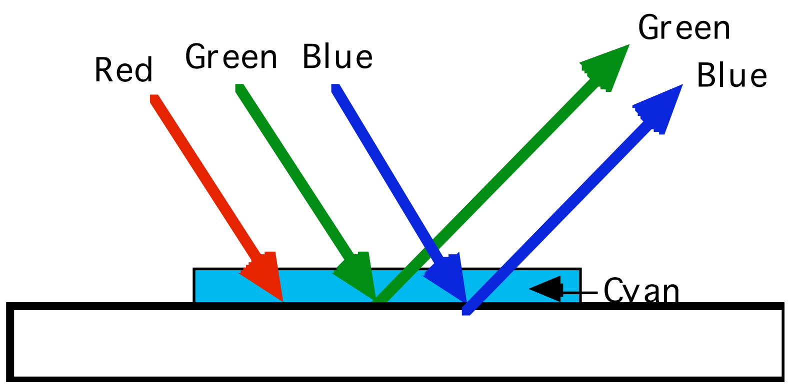
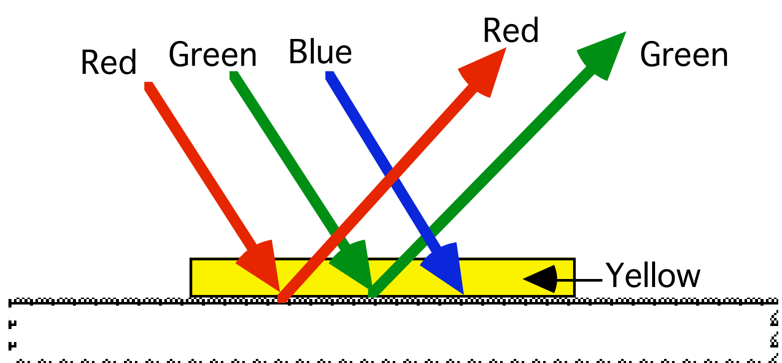
Cyan absorbs red light leaving
green and blue



Yellow absorbs blue light leaving
green and red



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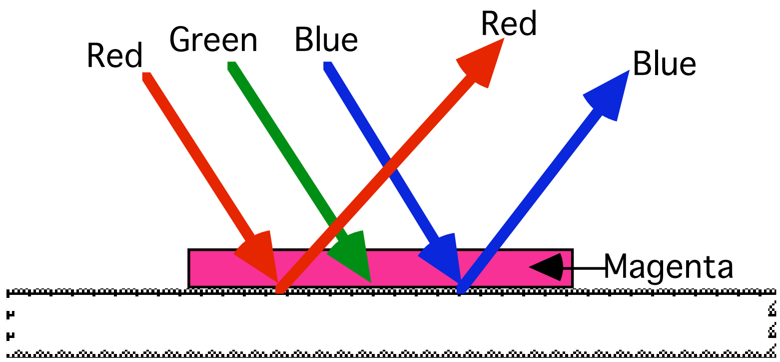
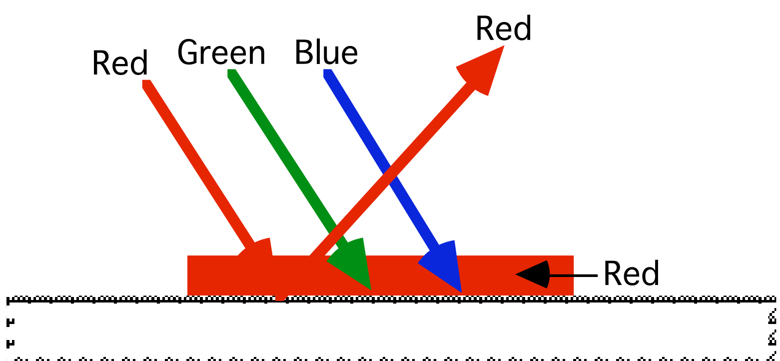
Magenta absorbs green light
leaving red and blue



Red absorbs green and blue light
leaving red



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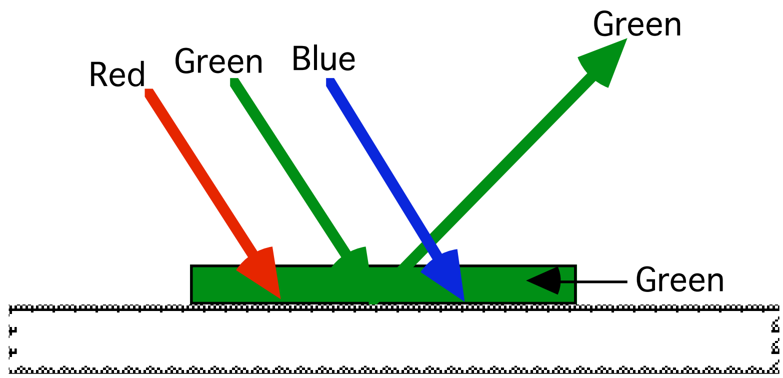
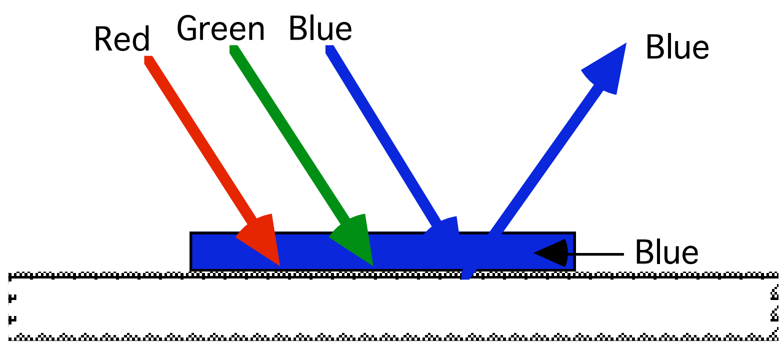
Green absorbs red and blue light
leaving green



Blue absorbs red and green light
leaving blue



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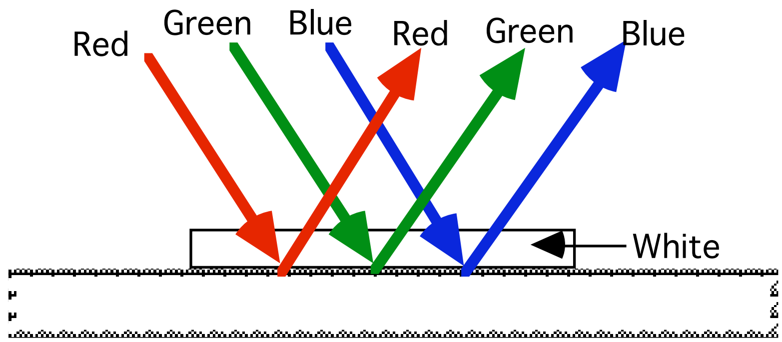
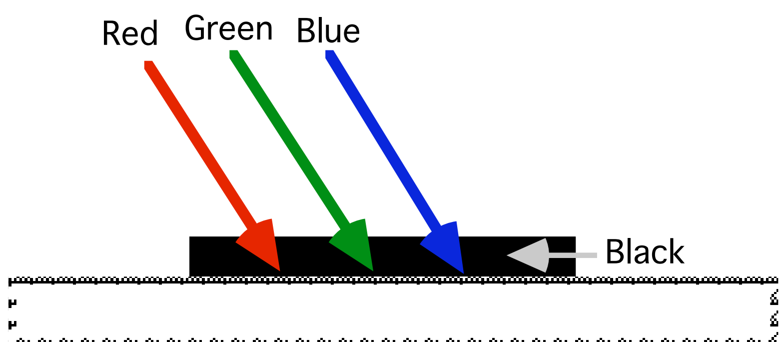
White absorbs no colors leaving
red, green and blue



Black absorbs red, green and
blue light leaving no light



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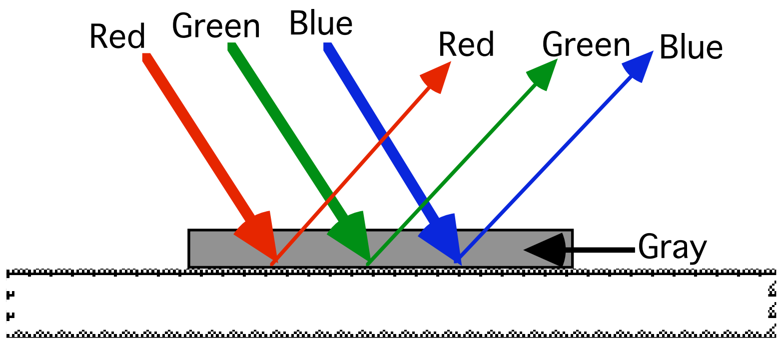
Gray absorbs some red,
green and blue light leaving
less red, green and blue light



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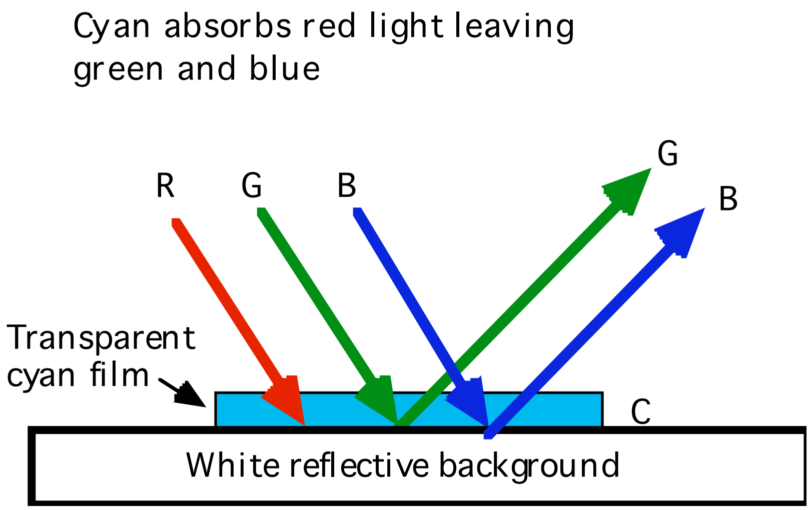
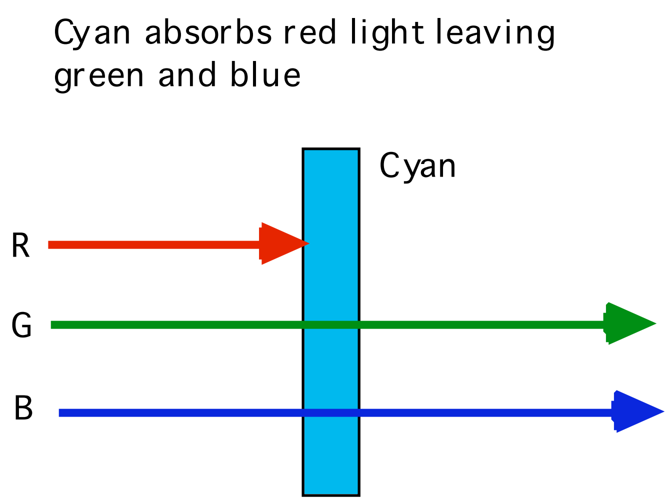
Recall the first diagram in this section that depicted what happens to white light when it is incident on a cyan film, sitting on a white background.



The diagram above demonstrates the subtractive color mixing of cyan in reflection: cyan subtracts red light from white light. The diagram indicates how this happens in reflection. Of course, subtractive color mixing also occurs in transmission, as shown in the diagram below. We see color of the object as cyan because only the green and blue components of the light strike our eyes.



There is, however, an important distinction that should be noted between the two previous diagrams. When the cyan film is placed on the

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white paper, the light must pass through the cyan film twice (from the air, through the cyan film, reflect off the white paper, again through the film, and then to our eye) before it reaches our eye. On the other hand, when we look through a cyan film, the light only passes through the cyan film once.

Since light passes through a film twice when it is on a piece of paper, the color will appear darker than when a film is held up in air in a room. Have the students notice how much lighter a colored film is when it is held up compared to its color when it is placed on a piece of paper. They might notice that the color of a double thickness of film held up in the air is pretty close to the color of a film placed on a piece of paper.

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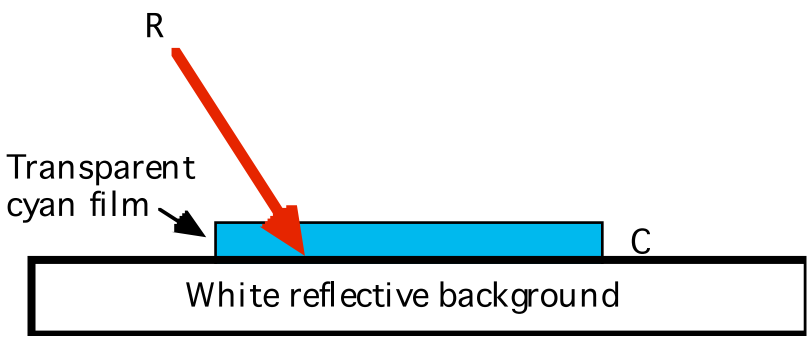
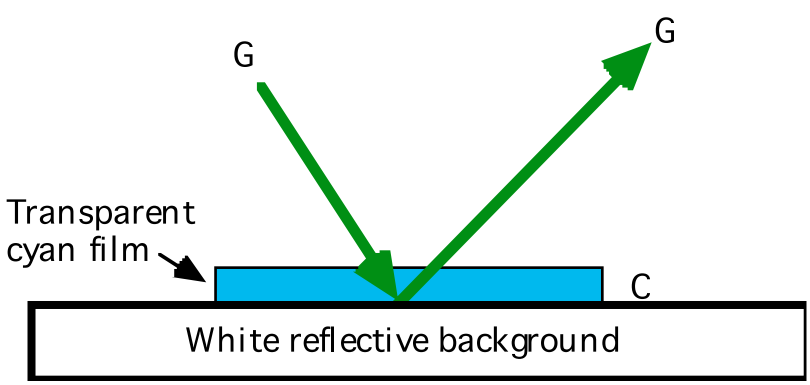
Note that the color of an object depends also on the color of the light that illuminates it, as shown in the examples below.

If a cyan film is illuminated by red light, it will appear black, because cyan absorbs red light.



If a cyan film is illuminated by green light, then it will appear green, because cyan only absorbs red light.



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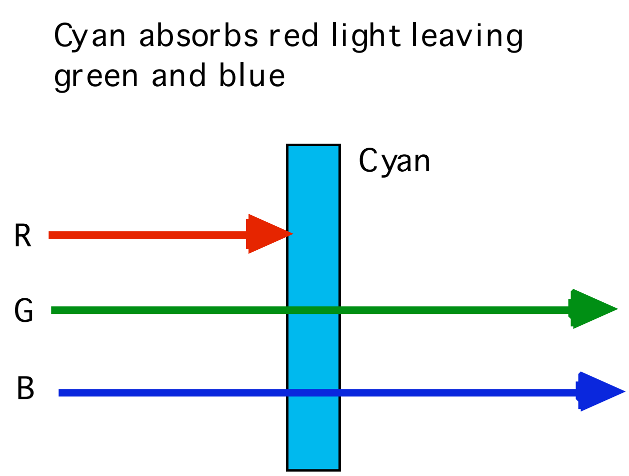
Teacher's Guide to Procedure:

1. Point out that the light that is given off by the sun, a light bulb, or fluorescent lamp is considered to be white (uncolored) light. Students should realize that objects that do not give off light are only seen because of light that is reflected off of them. In a dark room, you cannot see these objects. In a room lit by a typical light source, we see colored objects because of the way they reflect the white light that is striking them. This reflected light then enters our eye, causing our perception of the color of the object.

2. The cyan film turns the red film on the white paper black, so cyan absorbs red light.
3. The magenta film turns the green film on the white paper black, so magenta absorbs green light.
4. The yellow film turns the blue film on the white paper black, so yellow absorbs blue light.
5. See the earlier diagrams in the teacher's guide for this experiment

1. a. The monitor appears to be cyan.
b. The red dots or light sources on the monitor now appear dark. The cyan film absorbed the red part of the white light.
c. When white light strikes a cyan-colored object, the object appears to be cyan because it absorbs red light.
d. white - red = cyan
(white - red = (red + green + blue) - red = green + blue = cyan)
They should make a table like the one shown below.

The diagram should appear as follows:



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2. a. The monitor appears to be magenta.

b. The green dots or light sources on the monitor now appear dark. The magenta film absorbed the green part of the white light.

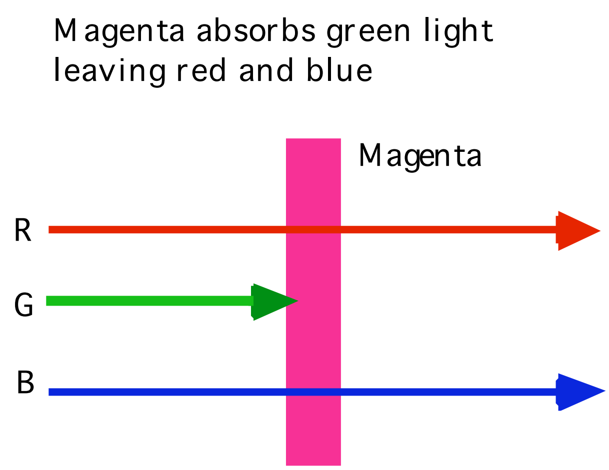
c. When white light strikes a magenta-colored object, the object appears to be magenta because it absorbs green light.

d. white - green = magenta

(white - green = (red + green + blue) - green = red + blue = magenta)

They should make a table like the one shown below.

The diagram should appear as follows:



3. a. The monitor appears to be yellow.

b. The blue dots or light sources on the monitor now appear dark. The yellow film absorbed the blue part of the white light.

c. When white light strikes a yellow-colored object, the object appears to be yellow because it absorbs blue light.

d. white - blue = yellow

(white - blue = (red + green + blue) - blue = red + green = yellow)

They should make a table like the one shown below.

The diagram should appear as follows:

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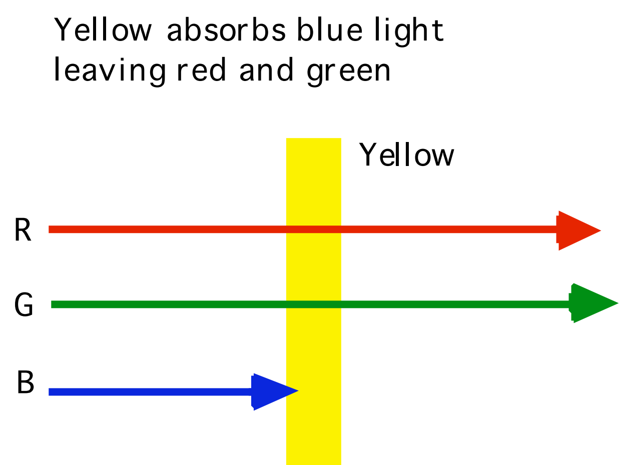


4. a. The monitor appears to be red.

b. The green and blue light sources on the monitor now appear dark. The red film absorbed the green and blue part of the white light.

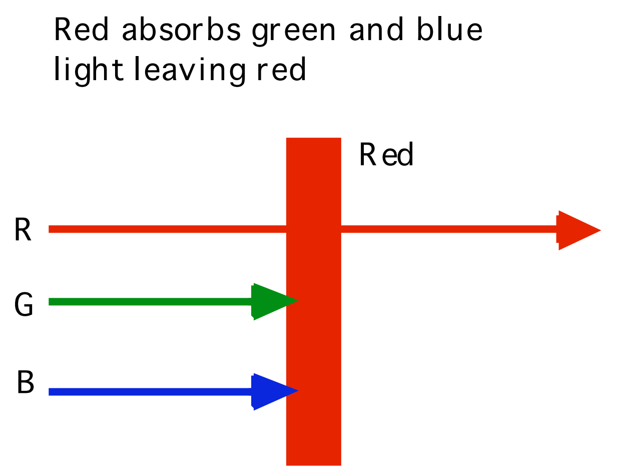
c. When white light strikes a red-colored object, the object appears to be red because it absorbs green and blue light.

d. white - green - blue = red

(white - green - blue = (red + green + blue) - green - blue = red)

They should make a table like the one shown below.

The diagram should appear as follows:



5. a. The monitor appears to be green.

b. The red and blue light sources on the monitor now appear dark. The green film absorbed the red and blue part of the white light.

c. When white light strikes a green-colored object, the object appears to be green because it absorbs red and blue light.

d. white - red - blue = green

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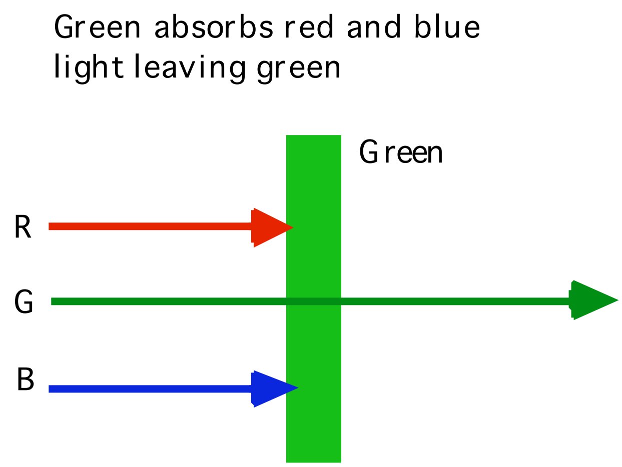
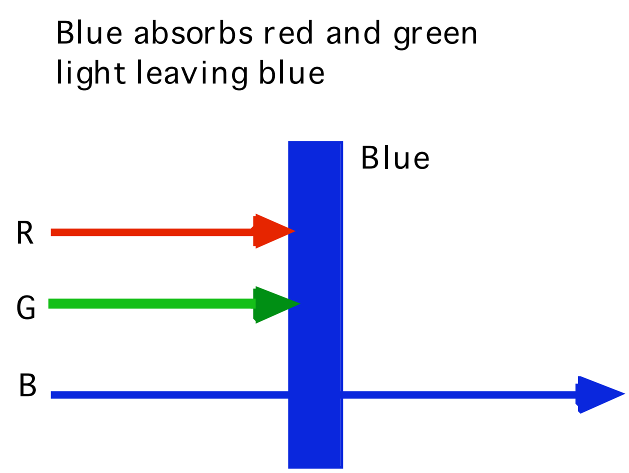
(white - red - blue = (red + green + blue) - red - blue = green)
They should make a table like the one shown below.
The diagram should appear as follows:



6. a. The monitor appears to be blue.
b. The red and green light sources on the monitor now appear dark. The blue film absorbed the red and green part of the white light.
c. When white light strikes a blue-colored object, the object appear to be blue because it absorbs red and green light.
d. white - red - green = blue
(white - blue = (red + green + blue) - red - green = blue)
They should make a table like the one shown below.
The diagram should appear as follows:



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How we see colored objects

Starting Color (WHITE)			Color of Film	Colors Remaining			Colors Absorbed		
R	G	B		R	G	B	R	G	B
X	X	X	CYAN		X	X	X		
X	X	X	MAGENTA	X		X		X	
X	X	X	YELLOW	X	X				X
X	X	X	RED	X				X	X
X	X	X	GREEN		X		X		X
X	X	X	BLUE			X	X	X	

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7. The red square becomes black because the cyan film absorbs red.
8. The green square stays green because the cyan film absorbs red.
9. The blue square stays blue because the cyan film absorbs red.
10. The cyan square stays cyan because cyan is a mixture of green and blue and the cyan film only absorbs red.
11. The magenta square becomes blue because magenta is a mixture of red and blue and the cyan film absorbs only absorbs red.
12. The yellow square becomes green because yellow is a mixture of red and green and the cyan film only absorbs red.
13. The red square stays red because the magenta film absorbs green.
14. The green square becomes black because the magenta film absorbs green.
15. The blue square stays blue because the magenta film absorbs green.
16. The cyan square becomes blue because cyan is a mixture of green and blue and the magenta film absorbs green.
17. The magenta square stays magenta because magenta is a mixture of red and blue and the magenta film absorbs green.
18. The yellow square becomes red because yellow is a mixture of red and green and the magenta film absorbs green.
19. The red square stays red because the yellow film absorbs blue.
20. The green square stays green because yellow film absorbs blue.
21. The blue becomes black because the yellow film absorbs blue.
22. The cyan square becomes green because cyan is a mixture of green and blue and the yellow film absorbs blue.
23. The magenta square becomes red because magenta is a mixture of red and blue and the yellow film absorbs blue.
24. The yellow square stays yellow because yellow is a mixture of red and green and the yellow film absorbs blue.

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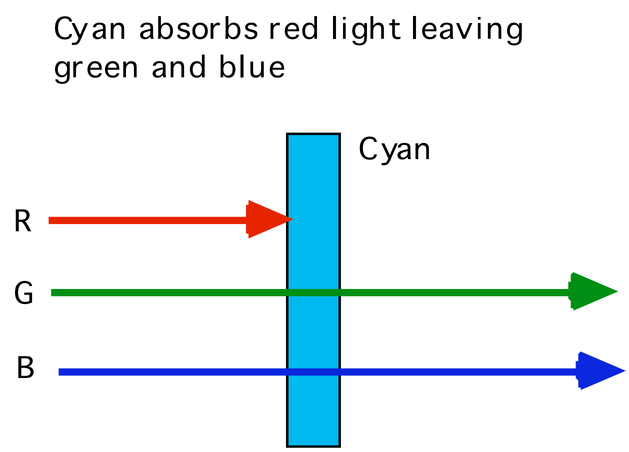
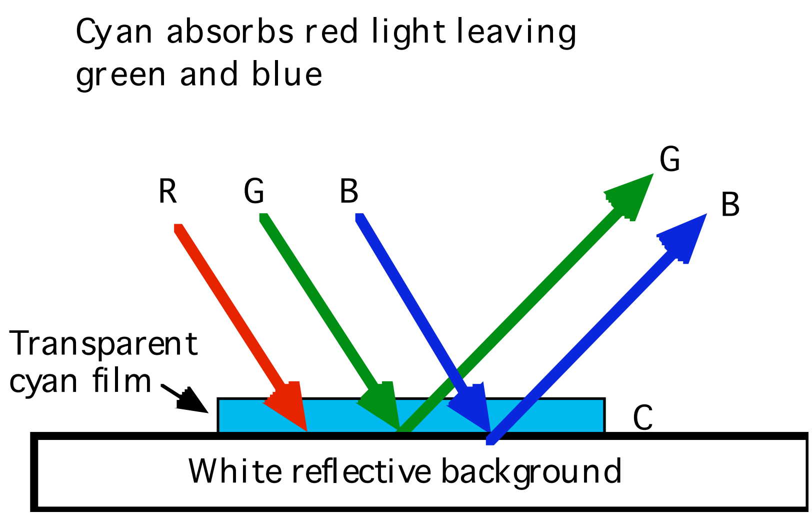
Teacher's Guide to Assessment:

1. Cyan-colored transparency film:



Cyan-colored paper:



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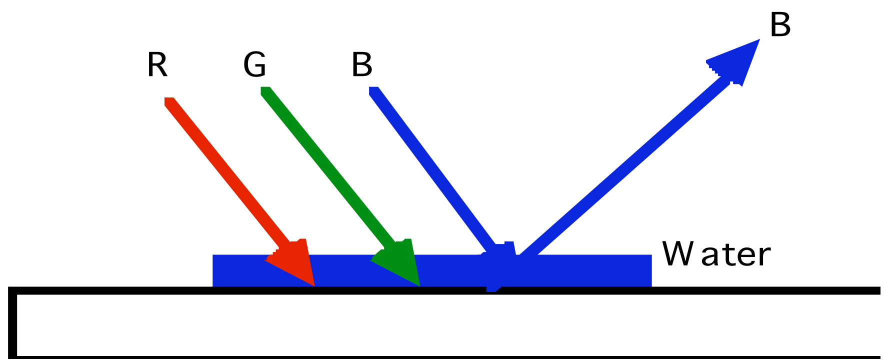
2. Water is blue, because it absorbs the red and green components of light.



As an interesting aside, the wavelength dependence of the absorption of light by water has apparently determined the wavelength range over which we can see. The absorption of light by water is low only in the relatively narrow visible range of the electromagnetic spectrum. In other words, water is quite transparent in the visible region of the spectrum and quite opaque at all other wavelengths. Water is more than 10^4 times more transparent in the visible region of the spectrum than it is at other wavelengths (like the infra-red and ultraviolet). Apparently, the eyes of sea animals evolved to take advantage of the transparency of water in the narrow region of the electromagnetic spectrum where water is relatively transparent. They could thus utilize the light that penetrated through the layer of water over them.

It is also interesting to note the significant differences between the human ear and eye. The frequency range over which the ear can hear varies by over a factor of 1000 (from about 20 Hz to about 20,000 Hz). So the wavelength range over which the ear can hear varies by a factor of 1000. In contrast, the visible region over which the eye can see extends from 400 to 700 nm, less than a factor of 2! In addition, the eye interprets multiple wavelengths of light as a single color, whereas the ear can distinguish multiple frequencies.

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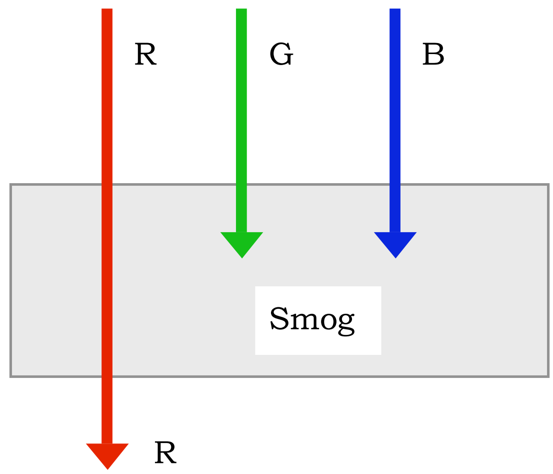
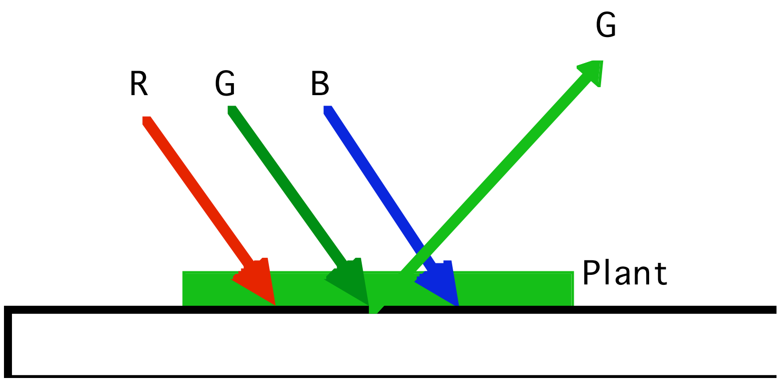
3. Smog appears to be red or reddish brown because it absorbs the green and blue components of light.



4. Plants appear to be green because they absorb the red and blue components of light.



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Benchmark 4E 8th grade: "Energy cannot be created or destroyed, but only changed from one form into another."
Benchmark 4E 8th grade: "Most of what goes on in the universe-from exploding stars and biological growth to the operation of machines and the motion of people-involves some form of energy being transformed into another. Energy in the form of heat is almost always one of the products of an energy transformation."
Benchmark 4E 8th grade: "Heat can be transferred though materials by the collisions of atoms or across space by radiation. If the material is fluid, currents will be set up in it that aid the transfer of heat."

5. Colored objects appear the colors that they do because of the colors that they subtract from the (usual) white light that strikes them. The remaining colors that enter our eye give our brain the sensation of color. But light has energy associated with it. What happens to the energy that the colored objects absorb? Since energy is conserved - it can neither be created or destroyed - something must happen to the energy associated with the light that is absorbed. The answer is that it is converted to heat.

The white shirt will be coolest because white does not absorb any colors - it reflects all of the light that strikes it.

The black shirt will be hottest because black absorbs all colors, red, green and blue- it reflects none of the light that strikes it. The energy associated with the red, green and blue light will be converted to heat.

6. The cyan, magenta, and yellow shirts will be cooler. The cyan shirt will absorb the red light and the energy associated with the red light will be converted to heat. The magenta shirt will absorb the green light and the energy associated with the green light will be converted to heat.
The yellow shirt will absorb the blue light and the energy associated with the blue light will be converted to heat.

The red, green, and blue shirts will be hotter. The red shirt will absorb the green and blue light and the energy associated with the green and blue light will be converted to heat. The green shirt will absorb the red and blue light and the energy associated with the red and blue light will be converted to heat. The blue shirt will absorb the red and green light and the energy associated with the red and green light will be converted to heat.

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7. In white light the banana is yellow, so it must absorb blue light and reflect red and green. Therefore the spotlight must contain some red light, but not any green light, so that the banana will appear red. The spotlights that contain red, but no green are the red spotlight and the magenta spotlight.

8. Blood appears red because it absorbs the green and the blue parts of the incident white light.

9. Gold and copper appear yellow because they absorb the blue part of the incident light, leaving the red and green components of the incident white light that are seen as yellow.

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Alternate Procedure

Use the tabletop light mixer to produce the colors instead of the computer monitor.

Using the table top light mixer in conjunction with a color wheel allows the student to readily determine which colors absorb which lights. It may be helpful to use a double layer of the transparent color wheels.

Benchmark 9B 12th grade: "Any mathematical model, graphic or algebraic, is limited in how well it can represent how the world works. The usefulness of a mathematical model for predicting may be limited by uncertainties in measurements, by neglect of some important influences, or by requiring too much computation."

1. Turn on the red light of the table top color mixer. Now place the color wheel over the red light and rotate it so that all of the colors of the wheel slowly pass over the red light. Notice the intensity of the red light as you do this. As the cyan part (actually from blue to green) of the color wheel passes over the red light, you will notice that it dims significantly. That is because cyan (and blue and green) absorbs red light.

2. Turn on the green light of the table top color mixer. Now place the color wheel over the green light and rotate it so that all of the colors of the wheel slowly pass over the green light. Notice the intensity of the green light as you do this. As the magenta part (actually from red to blue) of the color wheel passes over the green light, you will notice that it dims significantly. That is because magenta (and red and blue) absorbs green light.

3. Turn on the blue light of the table top color mixer. Now place the color wheel over the blue light and rotate it so that all of the colors of the wheel slowly pass over the blue light. Notice the intensity of the blue light as you do this. As the red section of the color wheel passes over the blue light, you will notice that it dims significantly. This is because the blue light is not a true blue, it is closer to cyan, which is a mixture of blue and green light. Therefore, since red absorbs both green and blue, only the red section of the color wheel dims the blue light.

Another Idea:

Generate a rainbow by using sunlight and a prism or diffraction grating or any other method available to you. Project the rainbow onto a piece of white paper. Place the colored films between the prism and the white paper, but near to the prism so that you can still see the rainbow on the white paper. Repeat procedure 1 but now find out which parts of the rainbow have been absorbed or darkened.

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Extra:

Using the knowledge gained in the first two experiments, have your students design and perform an experiment to demonstrate that the color of an object depends on the color of the incident light. Have your students investigate the importance of lighting in the visual perception of the color of clothes and makeup.

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Teacher's Guide

Experiment 3: Overlapping Cyan, Magenta, Yellow and Their Complementary Colors

Purpose:

To investigate subtractive color mixing using cyan, magenta and yellow and to investigate their respective complementary colors.

Discussion:

Overlapping colors of red, green and blue do not produce any color other than black or a very dark version of red, green, or blue. Thus, overlapping these colors only leads to dark shades of these colors, not new colors that are in between these colors.

Let's now consider what colors can be made using the colors cyan, yellow and magenta and overlapping them. Recall that cyan absorbs red, yellow absorbs blue and magenta absorbs green.

Table 3: Overlapping Cyan, Yellow and Magenta (/ = overlapping)

When white light strikes a surface with the color	These colors are absorbed			So are these colors reflected			So you see
	RED	GREEN	BLUE	RED	GREEN	BLUE	
CYAN (C)	X				X	X	CYAN
MAGENTA (M)		X		X		X	MAGENTA
YELLOW (Y)			X	X	X		YELLOW
C/Y	X		X		X		GREEN
C/M	X	X				X	BLUE
Y/M		X	X	X			RED
C/Y/M	X	X	X				BLACK
BLACK	X	X	X				BLACK

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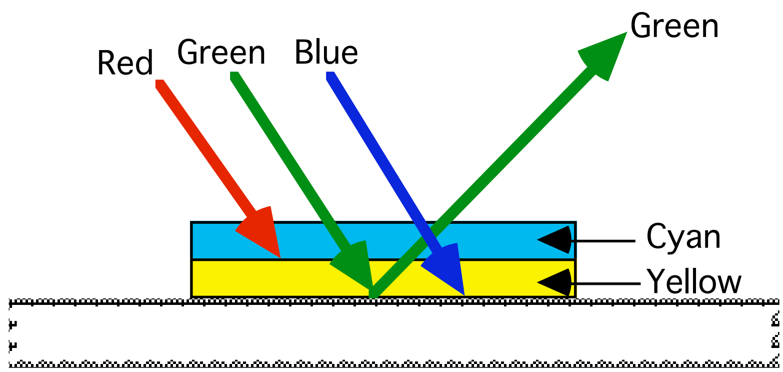
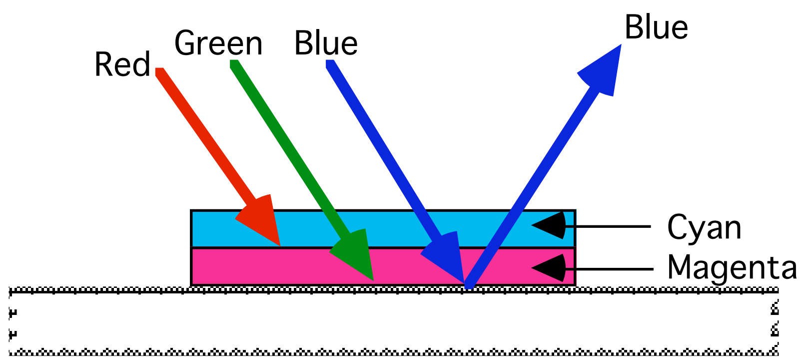
Cyan overlapping yellow yields green.



Cyan overlapping magenta yields blue



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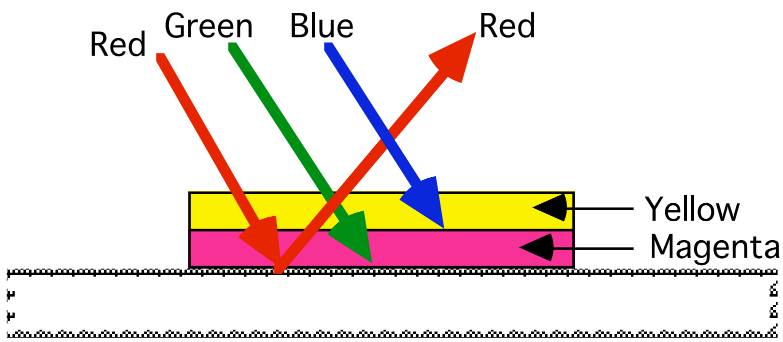
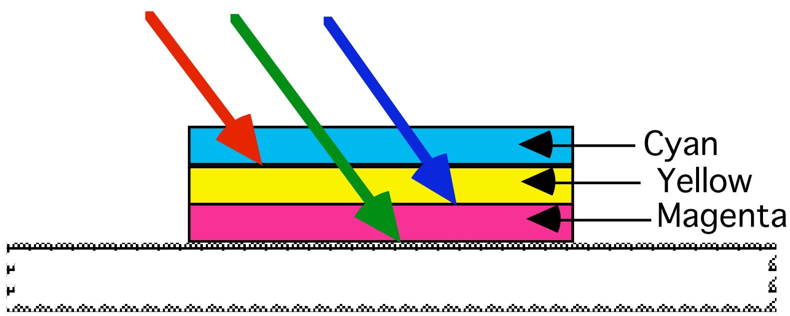
Yellow overlapping magenta yields red.



Cyan overlapping yellow overlapping magenta yields black.



From this table, it appears that overlapping two of the colors cyan, magenta and yellow (CMY) produces totally new colors: red, green or blue (RGB). In contrast, overlapping two of the colors red, green and blue leads to just dark shades of those colors or black. (The reason is that the colors CMY each only absorb one of the RGB colors, whereas the colors RGB each absorb two of the RGB colors.) Therefore, we can produce all of the colors that lie anywhere between CMY and RGB just by overlapping different amounts of CMY.

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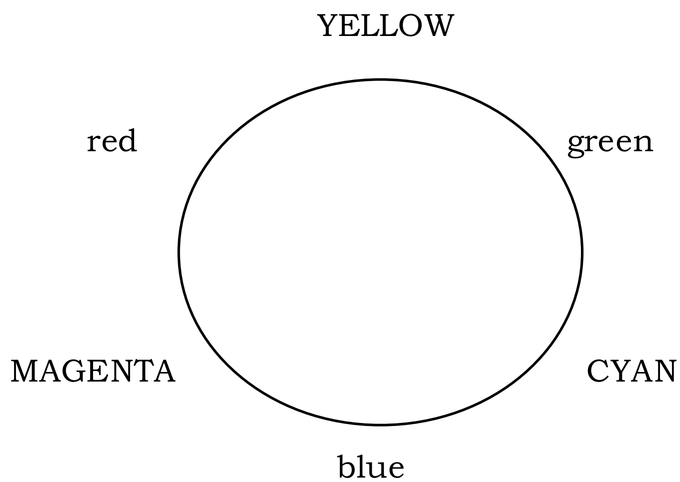
<u>Teacher's Guide to Procedure:</u>

1. As described.
2. Cyan absorbs red and yellow absorbs blue so the resultant color is green. The diagram was shown above.
White - Red - Blue = (Red + Green + Blue) - Red - Blue = Green.
3. Cyan absorbs red and magenta absorbs green so the resultant color is blue.
The diagram was shown above.
White - Red - Green = (Red + Green + Blue) - Red - Green = Blue.
4. Yellow absorbs blue and magenta absorbs green so the resultant color is red.
The diagram was shown above.
White - Blue - Green = (Red + Green + Blue) - Blue - Green = Red.
5.



The color wheel is the same as that developed in experiment 1, except that now the primary colors are cyan, magenta, and yellow instead of red, green, and blue.

6. Cyan absorbs red, yellow absorbs blue and magenta absorbs green so the resultant color is black.
The diagram was shown above.
White - Red - Blue - Green = (Red + Green + Blue) - Red - Blue - Green = Black.

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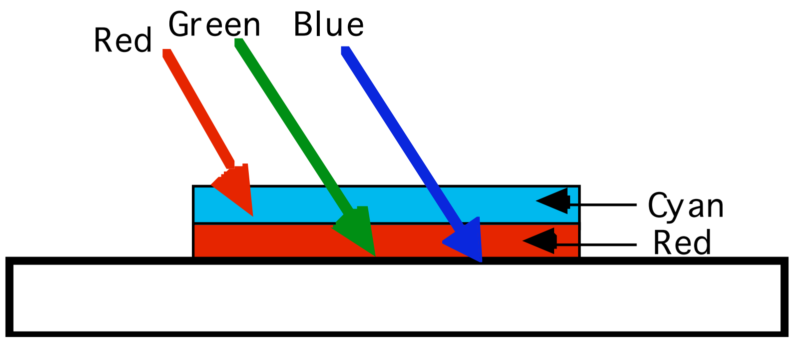
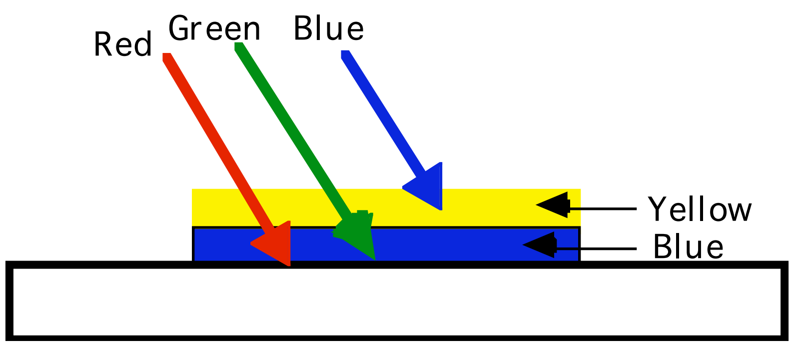
7. Cyan absorbs red, and red absorbs green and blue, so the resultant color is black. When two subtractive colors are combined to make black, they are said to be complementary colors. So cyan and red are complementary colors.
White - Red - Green - Blue = Black



8. Yellow absorbs blue, and blue absorbs red and green, so the resultant color is black. When two subtractive colors are combined to make black, they are said to be complementary colors. So yellow and blue are complementary colors.
White - Red - Green - Blue = Black



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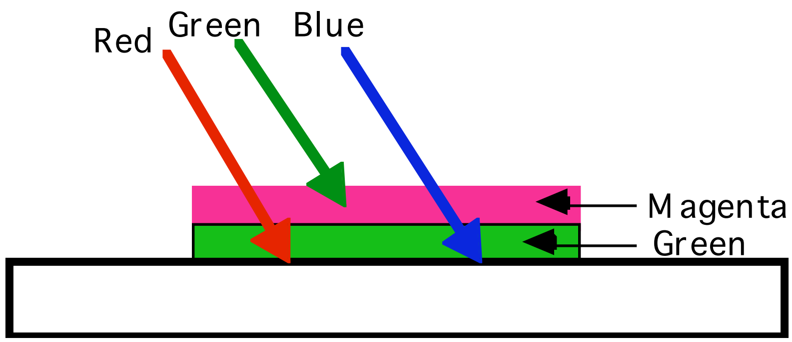
9. Magenta absorbs green, and green absorbs red and blue, so the resultant color is black. When two subtractive colors are combined to make black, they are said to be complementary colors. So magenta and green are complementary colors.
White - Red - Green - Blue = Black



10. Complementary colors are on opposite sides of the color wheel.
11. See the table above.
12. . Red absorbs green and blue, and yellow absorbs blue, so the resultant color is red.
13. Red absorbs green and blue, and blue absorbs red and green, so the resultant color is black.
14. Yellow absorbs blue and blue absorbs red and green, so the resultant color is black.
15. a. By overlapping red, yellow, and blue, only the additional colors of red or black can be obtained.

b. By overlapping cyan, magenta, and yellow, the additional colors of red, green, blue, and black can be obtained.

c. By overlapping red, green, and blue, only the additional color of black can be obtained.

Cyan, magenta, and yellow yield more colors when overlapped, and therefore would be the best 3 colors to use to generate additional colors. From this experiment, we can conclude that cyan, magenta, and yellow are the 3 primary colors of transparent films.

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Teacher's Guide to Assessment:

1. The complementary colors of pigments were shown above. They are (1) red and cyan; (2) magenta and green; and (3) yellow and blue.

The complementary colors of light are the same!

Red + Cyan = Red + (Green + Blue) = White

Magenta + Green = (Red + Blue) + Green = White

Yellow + Blue = (Red + Green) + Blue = White

2. a. No, because they each subtract one color from white light.

b. Yes. See diagrams above.

3. The primary colors of light are red, green, and blue. The primary colors of pigment are cyan, magenta, and yellow.

4._Earlier we stated that color is seen because our eyes contain 3 types of color receptors called cones. Each of the 3 types of cones is mainly sensitive to either red, green or blue. There is a relatively simple way to demonstrate this. You have probably seen this demonstration previously, but with the correct color wheel and knowledge of the correct complementary colors, it now can be properly explained.

Benchmark 4F 8th grade: "Human eyes respond to only a narrow range of wavelengths of electromagnetic radiation-visible light Differences of wavelength within that range are perceived as differences in color."

Stare at a red circle or other distinct shape for about 30 seconds. Then stare at a white piece of paper that is next to the circle. You should see a circle that is cyan, red's complementary color. The reason is that when you stare for a long time at the red circle, it makes the red cones tired. Therefore, when you switch your stare to the white sheet of paper, the red cones, which are tired, don't respond well and are not nearly as sensitive as the green and blue cones. The green and blue cones do respond normally and the green and blue cones together indicate that the color is cyan.

Stare at a yellow circle or other distinct shape for about 30 seconds. Then stare at a white piece of paper that is next to the circle. You should see a circle that is blue, yellow's complementary color. The reason is that when you stare for a long time at the yellow circle, it makes the red and green cones tired. Therefore, when you switch your stare to the white sheet of paper, the red and green cones, which are tired, don't respond well and are not nearly as sensitive as the blue cones. The blue cones do respond normally and the blue cones together indicate that the color is blue.

Similarly if you stare at a shape that is any color, you will see its complementary color as an afterimage. The complementary color is the one indicated using the color wheel described in this module.

<u>Historical note</u>: In the operating room, surgeons often stare for long times at bloody parts. If they looked away from the operating table at the white clothing of their colleagues, they would see the complementary afterimage of the red blood, which would be cyan. This tended to disturb the

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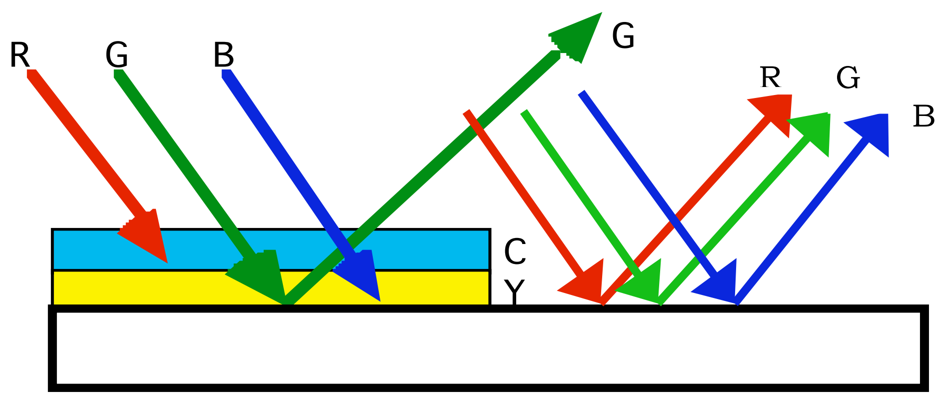
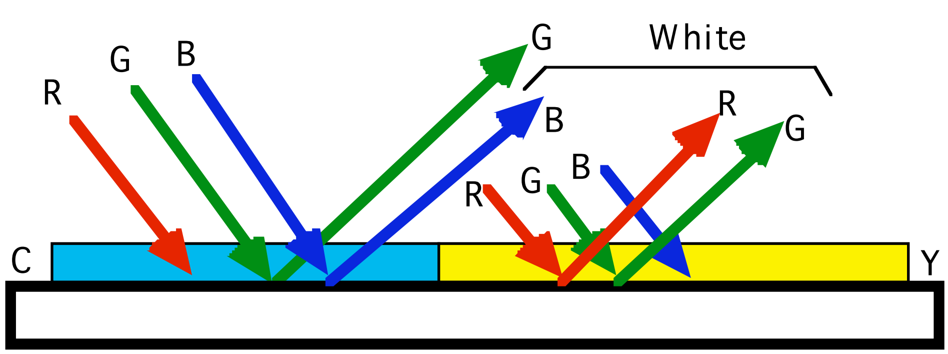
surgeons. The clothing now worn in operating rooms is light green or blue, so that the cyan afterimage is nearly eliminated - since it is difficult to see cyan on a cyan-colored background!

5. a. Cyan absorbs red and the yellow absorbs blue so that only green light is left from the area containing the 2 dots. The other area reflects all of the white light. This is shown schematically below. The resultant color is a light green (G+R+B+G), since white is being added to green.



Now let's consider the case of a C dot adjacent, but not overlapping a Y dot. What will be the resultant color? We know that C absorbs R, leaving G and B, while Y absorbs B, leaving R and G. So we will end up with G+B+R+G. Since R+G+B=White, this produces green + white or a light green. Thus, adjacent dots of C and Y results in a light green. This is shown schematically below.



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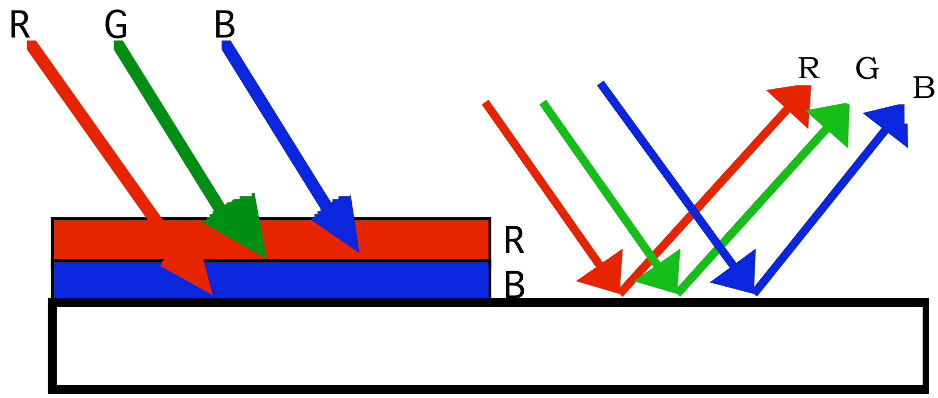
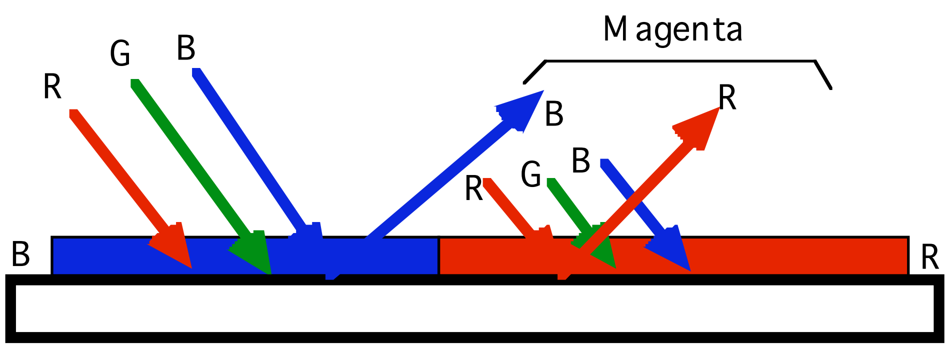
5. b. Red absorbs green and blue and the blue absorbs red and green so that no light is left from the area containing the 2 dots. The other area reflects all of the white light. This is shown schematically below. The resultant color is a gray, since white is being added to black.



Now let's consider the case of a R dot adjacent, but not overlapping a B dot. What will be the resultant color? We know that R absorbs G and B, leaving R. B absorbs R and G leaving B. So we will end up with R + B, or magenta. But the color will be a dark magenta, because only half of the magenta light is reflected that would have been reflected had a magenta ink covered the entire surface. Thus, adjacent dots of R and B results in a dark magenta. This is shown schematically below.



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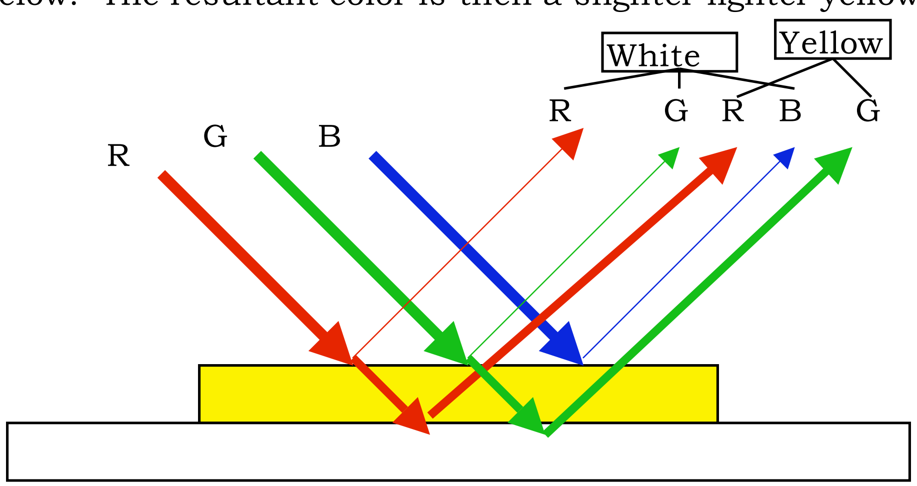
5c. Thus, when printing using red, green, or blue, very different colors result depending on whether the dots are overlapping or adjacent. Also note that if printers used the RGB system for printing, they could not make many colors, such as cyan, magenta, or yellow or light tints of these colors. When printing using cyan, magenta, or yellow, it doesn't matter if different colored dots overlap or are adjacent. The same color results.

6. As pointed out in the main color ideas section of this module, there are some simplifications that have been made. You or some of your students may have discovered one of these: namely that colored film A on top of colored film B may produce a different color than colored film B on top of colored film A. For example, a yellow film on a magenta film produces an orange-red color, whereas a magenta film on top of a yellow film produces the desired red color. The models that we have been using would predict that the order of the films doesn't matter - clearly this model has limitations. Let's see why.

Benchmark 9B 12th grade: "Any mathematical model, graphic or algebraic, is limited in how well it can represent how the world works. The usefulness of a mathematical model for predicting may be limited by uncertainties in measurements, by neglect of some important influences, or by requiring too much computation."

Consider a yellow film on a white piece of paper, as shown below, which is illuminated by white light. In the models discussed above, the blue light is perfectly absorbed by the yellow film, while the red and green light is perfectly transmitted through the film to the white piece of paper, which perfectly reflects the red and green back through the film.

In reality, some of the light is reflected at the top surface of the film. The red, green, and blue light that is reflected by the top surface of the film adds to make white light. The yellow film absorbs the blue light. The majority of the red and green light pass through the yellow film, reflect off the white paper, and then pass again through the yellow film, as shown below. The resultant color is then a slighter lighter yellow.



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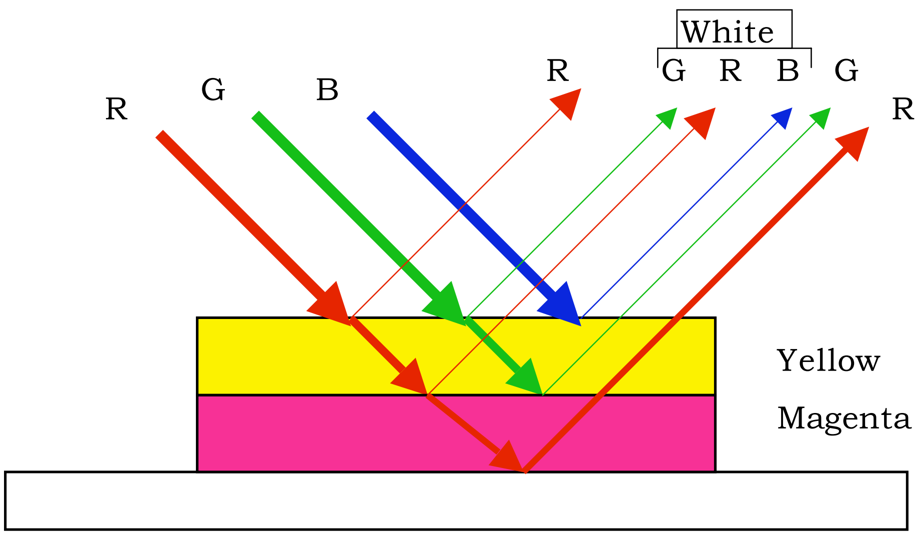
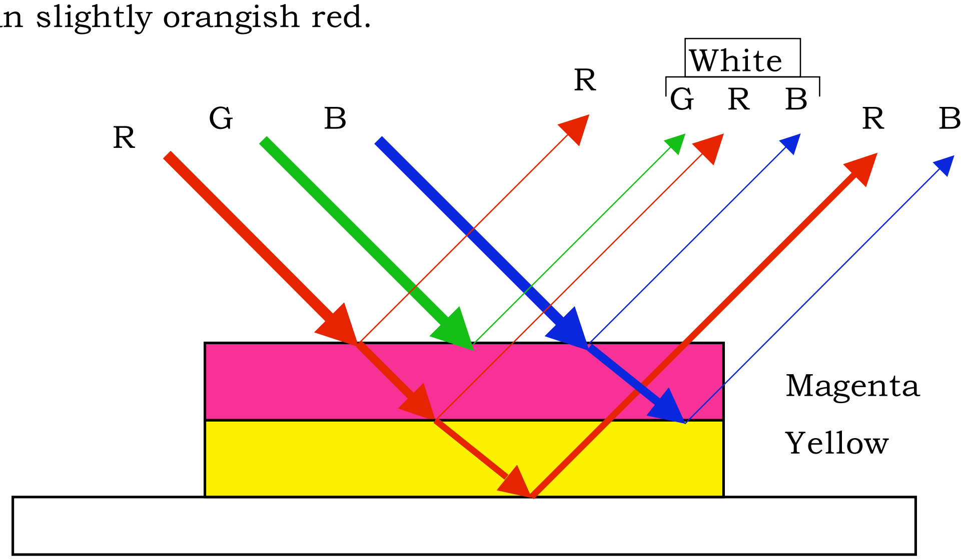
Now let's consider the case of a yellow film on a magenta film on a white piece of paper and the case of a magenta film on a yellow film on a white piece of paper.



Now let's add up the reflected colors to see what the resultant colors are: the thin red, green, and blue lights make white light, so they just make the resultant color appear lighter so we will ignore it. That leaves a thick red light, a thin red light, and a thin green light. The red and green thin lights add to make yellow light, so the resultant color is mostly red, but with some yellow added to it. So from our color wheel, this will appear to us as an slightly orangish red.



Now let's add up the reflected colors to see what the resultant colors are: the thin red, green, and blue lights make white light, so they just make the resultant color appear lighter so we will ignore it. That leaves a thick red light, a thin red light, and a thin blue light. The red and blue thin lights add to make magenta light, so the resultant color is mostly red, but with

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some magenta added to it. So from our color wheel, this will appear to us as a slightly deeper red or "magentaish" red.

7. For a film to appear blue, it must absorb most of the red and green light. Let's assume that the blue film absorbs 85% of the red (it transmits 15%) and 60% of the green light (it transmits 40%). Note that using the RGB model on the computer, a color defined by 100% blue, 15% red, and 40% green appears to be a blue color.

For a film to appear yellow, it must absorb most of the blue light. Let's assume that the yellow film absorbs 100% of the blue (it transmits 0%) light and absorbs none of the red or green light. Note that using the RGB model on the computer, a color defined by 0% blue, 100% red, and 100% green appears to be a yellow color.

When the two films are placed on one another, all of the blue is absorbed, and 15% of the red and 40% of the green light is transmitted. Using the RGB color model, a color defined by 15% red, 40% green, and 0% blue is a dark green color.

This analysis implies that the blue colors used by artists, while reflecting most or all of the blue light, also reflect more green light than red light.

The point of this assessment is for the students to realize that because colors are not pure or perfect, what appears to be blue or yellow can actually be a mixture of colors, resulting in color mixing that is more complicated than the simple color model predicts.

8. For a film to appear blue, it must absorb most of the red and green light. Let's assume that the blue film absorbs 0% of the blue (it transmits 100%), 85% of the red (it transmits 15%) and 60% of the green light (it transmits 40%). Note that using the RGB model on the computer, a color defined by 100% blue, 15% red, and 40% green appears to be a blue color.

For a film to appear red, it must absorb most of the blue and green light. Let's assume that the red film absorbs 0% of the red (it transmits 100%), and 85% of the green light (it transmits 15%), and 70% of the blue (it transmits 30%). Note that using the RGB model on the computer, a color defined by 100% red, 15% green, and 30% blue appears to be a red color.

When the two films are placed on one another, 30% (100% of 30%) of the blue, 15% (100% of 15%) of the red and 6% of the green (40% of 15%) light is transmitted. Using the RGB color model, a color defined by 15% red, 6% green, and 30% blue is a dark purple color.

The point of this assessment is for the students to realize that because colors are not pure or perfect, what appears to be blue or red can actually be a mixture of colors, resulting in color mixing that is more complicated than the simple color model predicts.

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Note that this assessment can be used to demonstrate another aspect of color math, namely that when two colored films are overlapped, then color multiplication can be used to predict the resultant color.

The blue film transmits 100% of the blue light, 15% of the red light and40% of the green light. To use color multiplication, these percentages should be written in decimal form. So the blue film transmits 0.15 red, 0.40 green, and 1.00 blue.

The red film transmits 1.00 red, 0.15 green, and 0.30 blue.

When the two films are placed on one another, the light transmitted is given by the product of the transmittances:

Transmitted red light = (0.15) x (1.00) = 0.15

Transmitted green light = (0.40) x (0.15) = 0.06

Transmitted blue light = (1.00) x (0.30) = 0.30

Using the RGB color model, a color defined by 15% red, 6% green, and 30% blue is a dark purple color.

Extra:

Demonstrate subtractive color mixing (or the CMY color model using a color model program that might be available on your computer.

Example 1:

Use the computer program Microsoft PowerPoint 4.0 for Macintosh (with MAC OS 8). Select the "Text Color" tool in the tool bar and select "Other Color." Then select "More Colors." Then select the CMYK Picker. Using the cyan/magenta/yellow/black (CMYK) color model, verify the subtractive color mixing described in this Experiment.

Example 2:

Use the computer program ClarisWorks 4.0 for Macintosh (with MAC OS 8). Select Painting. In the Painting program, select and drag the Fill Color palette into the document area so it is permanently displayed. Then double click on any color square in the palette. Then select the CMYK Picker. Using the cyan/magenta/yellow/black (CMYK) color model, verify the subtractive color mixing described in this Experiment.

Example 3:

Download the following Java Applet from the World Wide Web:
http://mc2.cchem.berkeley.edu/Java/absorption/absorption.html
Use the cyan/magenta/yellow color model to verify the color mixing described in this experiment.

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White - x = Blue

On a white sheet of paper, how can the red and green components of white light be subtracted out to leave just blue? One way is to place a blue transparency on the white paper. Since the blue transparency absorbs both red and green light, only blue light remains. Another way is to individually subtract the red and the green light. The way to do this is to place a cyan film (which absorbs the red) on top of a magenta film (which absorbs the green)

Demonstration: Bring in a Zip Lock bag which has "color-loc" to show that the bag has been properly closed. Notice that they use the primary subtractive colors.

Extra:

Note that artists and advertisements often use complementary colors because of their striking contrast. Matisse is one of the few masters to use the correct complementary colors in his paintings, for example magenta and green, not red and green. As a possible exercise, have your students bring in examples of art or advertisements in which complementary colors are used.

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Teacher's Guide

Experiment 4: Overlapping Gradients of Cyan, Magenta, Yellow, and Black

Purpose:

To investigate subtractive color mixing and the large range of colors that can be produced by overlapping gradients of cyan (C), magenta (M), yellow (Y), and black (K). This will clarify how color printers can use the 4 colors above to generate a wide variety of colors, as will be done in the next experiment. and black gradient transparency rectangles

Discussion:

In the previous section, we saw how combinations of the primary subtractive colors cyan, magenta, and yellow could be used to generate the red, green, blue, and black. But how are all the other colors like browns, orange, purple, etc. made? In this experiment, students will discover how overlapping different percentages of cyan, magenta, yellow, and black can generate almost all other colors. It will tend to quantify their understanding of color mixing.

Teacher's Guide to Procedure:

1. As stated. Encourage the discussion of fractions of color, or shades of color.
2. As stated. This might include the color of a desk, pencil, book cover, folder, shirt, sweater, pants, etc.
3. As stated.
4. The percentages of cyan, magenta, yellow, and black are noted on the square pieces. The percentages should be measured using a ruler using the strips, since the coverage of the color varies linearly from 0 to 100 % over the length of strip.
5. An example might be Orange = M50 + Y100 +K5
(50% magenta, 100% yellow, and 5% black)
6. These 4 colors are used in 4 color printing. By varying the percentages of these 4 colors, almost all colors can be reproduced. The color dots might overlap or they might be adjacent. Using RBG and K could only produce light and dark shades of R, G, and B, so they would not be useful colors for printers to use, unless the printer just wanted to make those colors.

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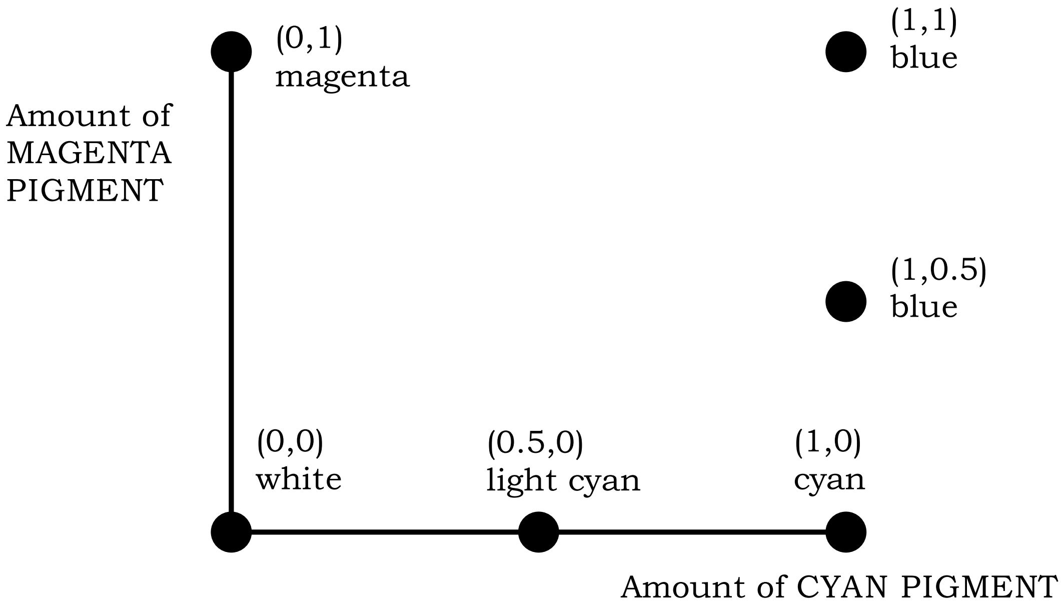
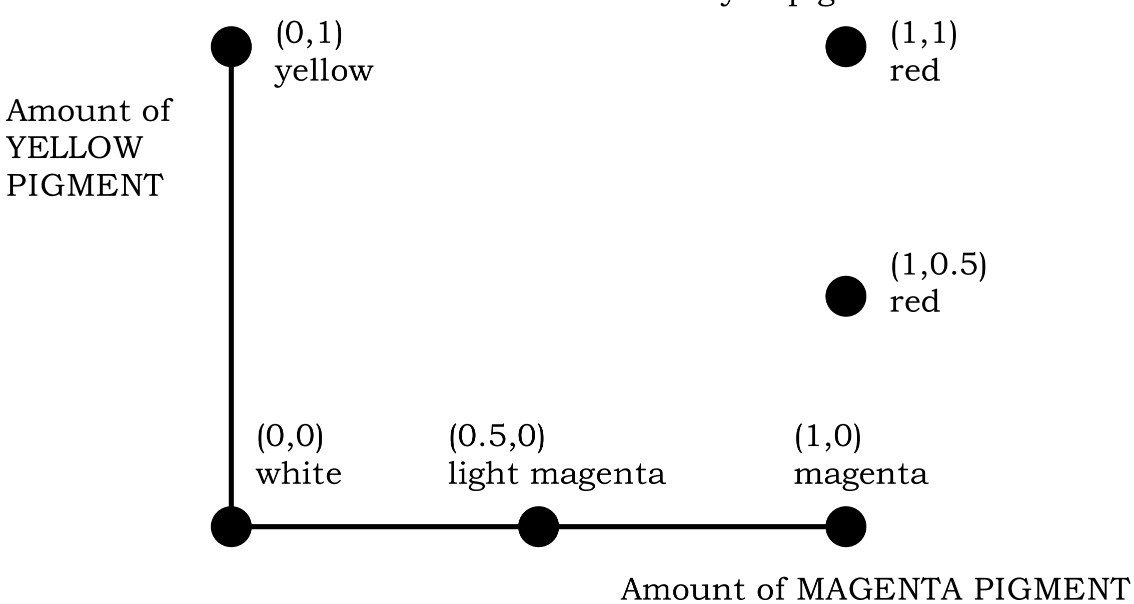
Teacher's Guide to Assessment:

1. This model does not include colors due to yellow pigments.



2. This model does not include colors due to cyan pigments.



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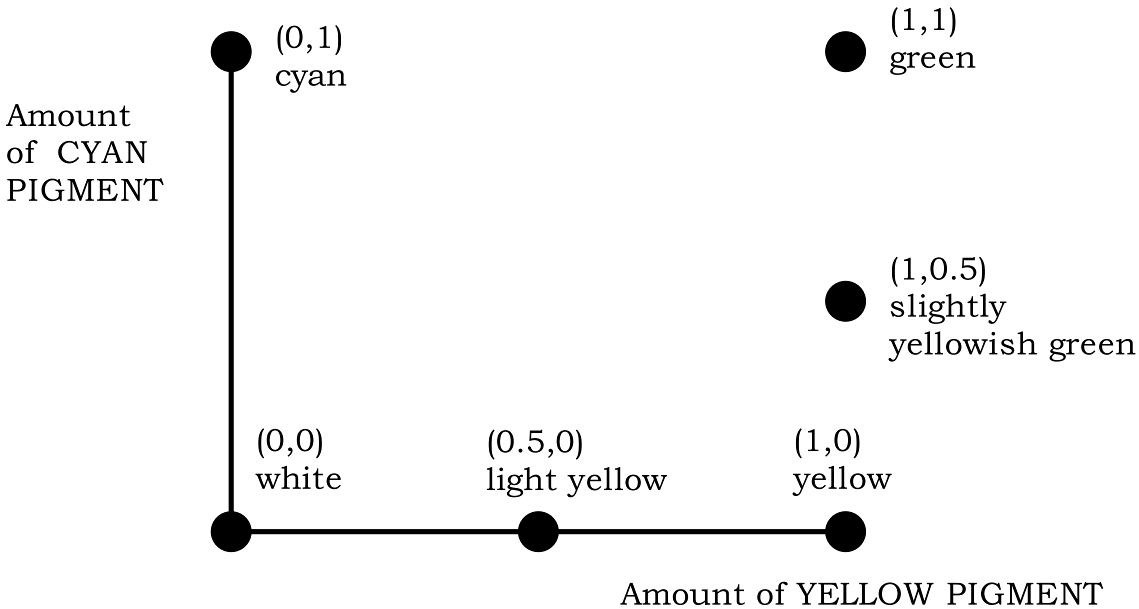
3. This model does not include colors due to magenta pigments.



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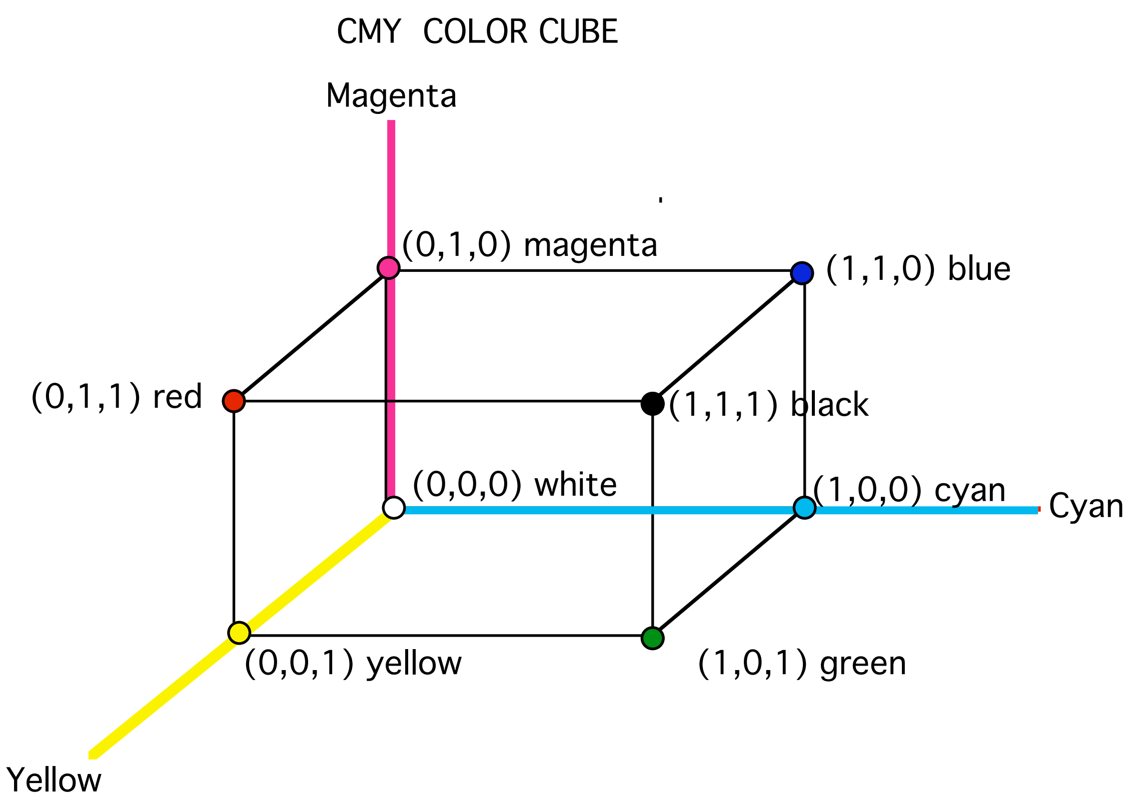
4. A way to describe subtractive color mixing is to use the a 3-dimensional coordinate system, the x, y and z axes , where the x-axis is the amount of cyan in the pigment, the y-axis is the amount of magenta in the pigment and the z-axis is the amount of yellow in the pigment. In this model, we have the following colors:

(x,y,z) = (cyan, magenta, yellow).
(0,0,0) = white
(1,1,1) = black
(1,0,0) = cyan
(0,1,0) = magenta
(0,0,1) = yellow
(1,1,0) = blue
(0,1,1) = red
(1,0,1) = green



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Note that for complementary overlapping pigments, the sum of the coordinates is (1,1,1), the same as black.

Note that these dimensions define a color cube for subtractive color mixing. The color wheel is obtained from the color cube by continuously traversing around the color cube subject to the following conditions:

- One of the coordinates always has a value of 1
- One of the coordinates always has a value of 0
- One of the coordinates always has a value that is greater than or equal to 0 and less than or equal to 1.

A three dimensional model of the color cube can be seen (and purchased) at the following address.
http://www.colorcube.com/

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Teacher's Guide

Experiment 5: Color Printing using CMY

Purpose:

To investigate how commercial colored pages are printed using cyan, magenta and yellow inks.

Discussion:

Printers use cyan, magenta and yellow dots to generate color pictures. They may also use black dots for text or to produce a dark black. It may be advantageous for the printer to print black using black ink instead of overlapping cyan, magenta, and yellow inks. Notice that the color ink jet printers have a color cartridge with three types of ink: cyan, yellow and magenta. They also have a black ink cartridge for black text or pictures.

Color printing of intermediate colors is done using a combination of adjacent and overlapping dots of cyan, magenta, and yellow.

Therefore, in printing, the colors CMY are produced using the ink colors CMY. The colors RGB are produced by overlapping two of the CMY inks, namely red = Y/M, green = C/Y and blue = C/M. The color black can be produced by overlapping C, Y, and M; or by using black ink. Colors between each of these can be produced by using adjacent dots of different colors, as explored in the previous experiment. Increasing the percentage of black area darkens the color, while increasing the percentage of white area lightens the color.

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Teacher’s Guide to Procedure:

1. Their predictions should be quite accurate if they understood Experiment 4.
2. As stated.
3. Many answers are possible. Typical examples are shown below.

By eye	In micro-scope	In micro-scope	In micro-scope	In micro-scope	Visually-CMYK	Visually CMYK	Visually CMYK	Visually CMYK
Color observed	% area covered by cyan dots	% area covered by magenta dots	% area covered by yellow dots	% area covered by black dots	% C (using gradient strip)	% M (using gradient strip)	% Y (using gradient strip)	%K (using gradient strip)
blue	50	50			100	100		
dark blue	50	50		50	100	100		50
light blue	25	25		25	50	50		

Benchmark 4D 2nd grade: “Objects can be described in terms of the materials they are made of (clay, cloth, paper, etc.) and their physical properties (color, size, shape, weight, texture, flexibility, etc.).”
Benchmark 4D 5th grade: “Materials may be composed of parts that are too small to be seen without magnification.”
Benchmark 4D 5th grade: “When a new material is made by combining two or more materials, it has properties that are different from the original materials. For that reason, a lot of different materials can be made from a small number of basic kinds of materials.”
Benchmark 11A 2ndgrade: “Most things are made of parts.”
Benchmark 11A 5 th grade: “In something that consists of many parts, the parts usually influence one another.”
Benchmark 11A 12th grade: “A system usually has some properties that are different from those of its parts, but appear because of the interaction of those parts.”
Benchmark 11B 8th grade: “Models are often used to think about processes that happen too slowly, too quickly, or on too small a scale to observe directly, or that are too vast to be changed directly, or that are potentially dangerous.”

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4. Printed colors are made using cyan, magenta, yellow, and often black dots. Black or grays can be made using either black ink or using cyan/magenta/yellow. Varying the ratio of these inks produces intermediate colors. Varying the density of the dots on the white background makes lighter colors. Darker colors are made by increasing the density of the dots or by adding more black to the background.

5. Color ink jet printers use color cartridges with cyan, magenta, and yellow inks and a black cartridge with black ink. They use these colors because cyan, magenta, and yellow are the primary colors of printing and these 3 primary colors allow the widest range of colors to be made.

6. Color film consists of blue sensitive, green sensitive, and red sensitive emulsion layers stacked on one another. During the development of the color photograph, these layers are converted to layers of yellow, magenta, and cyan dyes.

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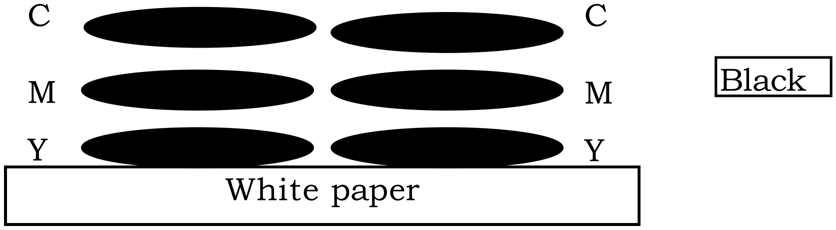
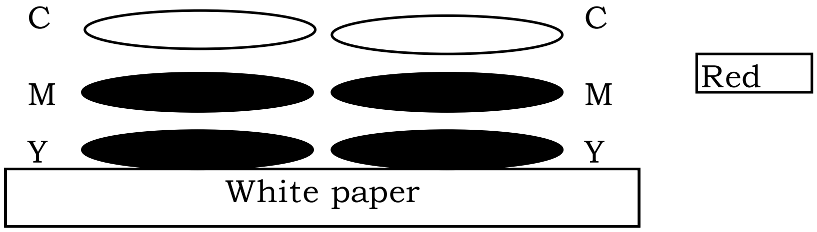
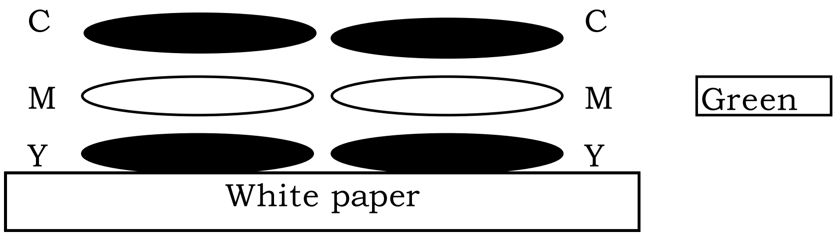
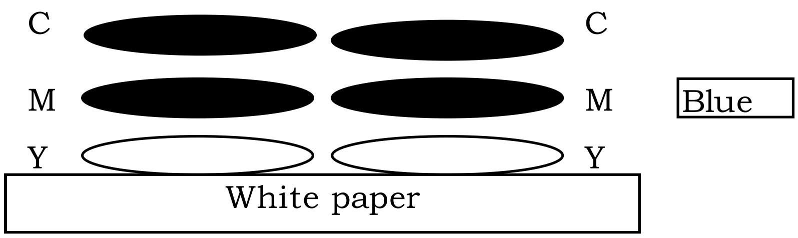
Teacher's Guide to Assessment:

1.









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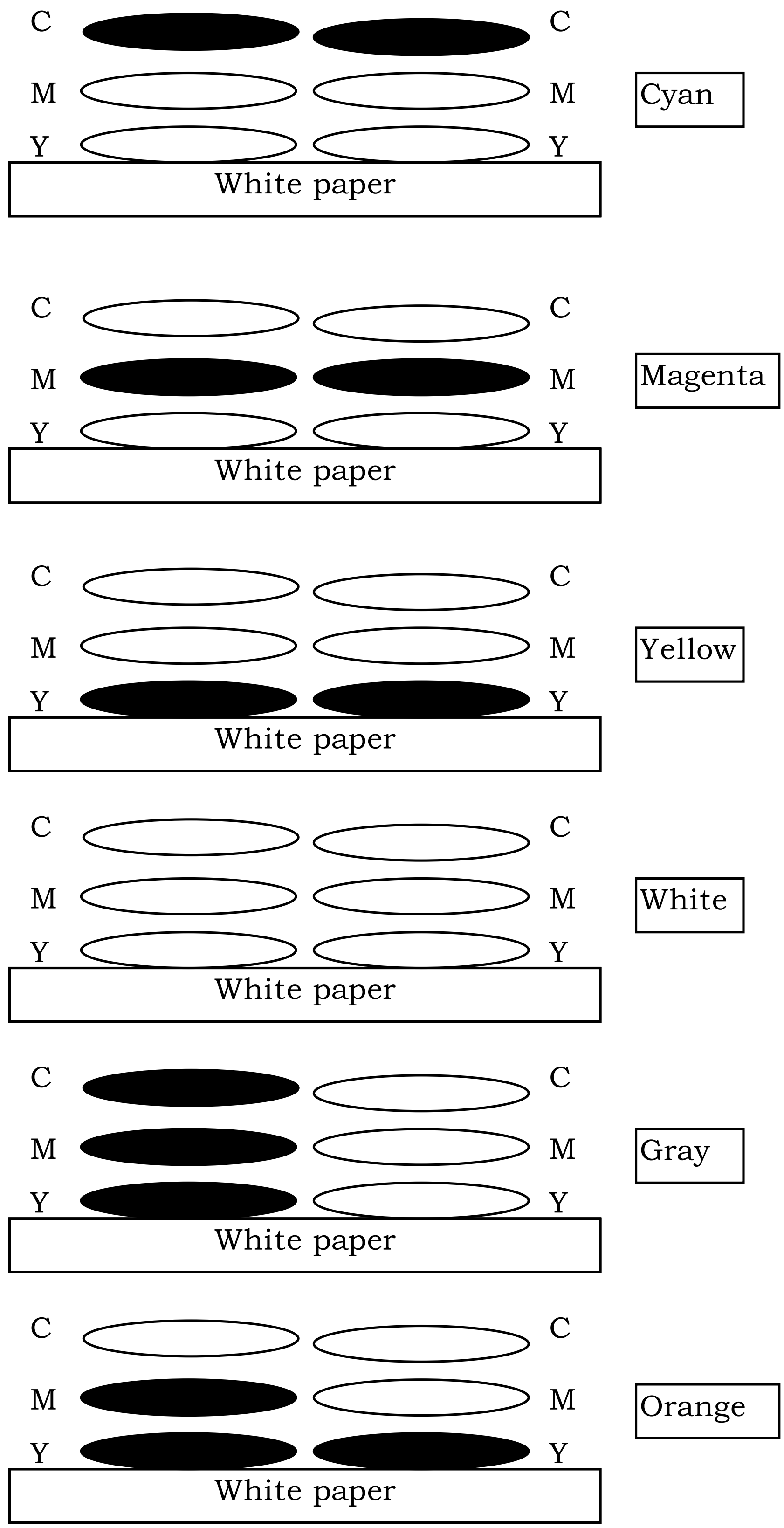

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Extra:

Many color pages contain small samples of the primary subtractive colors cyan, magenta, and yellow so that the printer can calibrate his primary colors against standards to ensure that the correct colors are being printed. Proper alignment of the colors is also checked by using calibration crosses and other types of marks.

Examples may be found on the top side flap of Kellogg's Crispix cereal, the top side flap of Post Honey Bunches of Oats cereal, the top side flap of Girl Scout Thin Mint cookies, and on bottom of many pages of Parade Magazine, a supplement to most Sunday newspapers, and many other places.

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Teacher's Guide

Experiment 6: Mixing RGB or CMY Colors with the Color Wheel

Purpose:

To investigate complementary colors using the color wheel.
To compare the range (or gamut) of colors can be made using different starting colors.

Teacher's Guide to Discussion:

1. As stated.
2. The colors are all black because the complementary colors of the two color wheels are overlapping.
3. The only colors are red and dark reds and black. The color range is limited to about 1/3 of the circumference of the color wheel. Since red absorbs green and blue, only the reds can be made by mixing red with all of the other colors.

This experiment also demonstrates that a red film absorbs its complementary color cyan. In other words, red absorbs green and blue. Therefore it turns the green, cyan, and blue parts of the color wheel black, since the red film absorbs these colors.
4. The only colors are green and dark greens and black. The color range is limited to about 1/3 of the circumference of the color wheel. Since green absorbs red and blue, only the greens can be made by mixing green with all of the other colors.

This experiment also demonstrates that a green film absorbs its complementary color magenta. In other words, green absorbs red and blue. Therefore it turns the red, magenta, and blue parts of the color wheel black, since the green film absorbs these colors.
5. The only colors are blue and dark blues and black. The color range is limited to about 1/3 of the circumference of the color wheel. Since blue absorbs red and green, only the blues can be made by mixing blue with all of the other colors.

This experiment also demonstrates that a blue film absorbs its complementary color yellow. In other words, blue absorbs red and green. Therefore it turns the red, yellow, and green parts of the color wheel black, since the blue film absorbs these colors.
6. The colors range from dark blue through dark green. The color range extends to about 2/3 the circumference of the color wheel. Since cyan

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absorbs only red, all of the blues and greens can be made by mixing cyan with all of the other colors.

This experiment also demonstrates that a cyan film absorbs its complementary color red. In other words, cyan absorbs red. Therefore it turns the red part of the color wheel black, since the cyan film absorbs this color.

7. The colors range from dark blue through dark red. The color range extends to about 2/3 the circumference of the color wheel. Since magenta absorbs only green, all of the blues and reds can be made by mixing magenta with all of the other colors.

This experiment also demonstrates that a magenta film absorbs its complementary color green. In other words, magenta absorbs green. Therefore it turns the green part of the color wheel black, since the magenta film absorbs this color.

8. The colors range from dark red through dark green. The color range extends to about 2/3 the circumference of the color wheel. Since yellow absorbs only blue, all of the reds and greens can be made by mixing yellow with all of the other colors.

This experiment also demonstrates that a yellow film absorbs its complementary color blue. In other words, yellow absorbs blue. Therefore it turns the blue part of the color wheel black, since the yellow film absorbs this color.

9. Artists often choose to use colors similar to cyan, magenta, and yellow, because mixing these 3 colors produces a wider range of colors than a different group of 3 colors.

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Teacher's Guide to Assessments:

1. Both the new and the traditional color wheels are shown below. Next to each color are graphical representations of how that color is made using light. For example, yellow consists of 100% red and 100% green light and 0% blue light.

Benchmark 11B 2ndgrade: "A model of something is different from the real thing but can be used to learn something about the real thing."

Also note that the new color wheel consistently changes color as we move around the color wheel. In terms of number of boxes filled, the new color wheel changes from: yellow (2 boxes filled) to green (1 box filled) to cyan (2 boxes filled) to blue (1 box filled) to magenta (2 boxes filled) to red (1 box filled). In contrast the traditional color wheel changes inconsistently from: yellow (2 boxes filled) to green (1 box filled) to blue (1 boxes filled) to violet (1.5 box filled) to red (1 boxes filled) to orange (1.5 boxes filled).

2. Red, yellow, and blue do not produce as wide a range of colors as cyan, magenta, and yellow. Using red, yellow, and blue, colors such as cyan and magenta cannot be produced.

3. Note that for the new color wheel, colors that are across from each other (on the diameter) are complementary. For example, viewing this from an additive color point of view, the R and G boxes are filled for yellow and the B box is filled for blue. Viewing this from the subtractive color point of view, the B box is unfilled for yellow (yellow subtracts blue) and the R and G boxes are unfilled for blue (blue subtracts red and green).

Note that colors across from each other in the traditional color wheel are not complementary.

Also point out to your students that models change as new information is learned. The old color wheel and primary colors that we were taught (and is still often taught) was incorrect. Our new data has demonstrated that the new color wheel is a better model for color mixing than the old traditional color wheel.

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4. a. Placing the cyan sheet over the color wheel turns the red part of the color wheel dark. So the cyan sheet absorbs red light.

Placing the magenta sheet over the color wheel turns the green part of the color wheel dark. So the magenta sheet absorbs green light.

Placing the yellow sheet over the color wheel turns the blue part of the color wheel dark. So the yellow sheet absorbs blue light.

Placing the cyan, magenta, and yellow sheets over a white piece of paper absorbs all of the incident white light, turning the white piece of paper black where the three films overlap. So the incident white light must have been composed of red, green, and blue light. (Note that placing any two of these sheets over one another does not produce black)

b. In part a, we showed that R + G + B = White.

- So R + G = White - B
  So to make R + G, we need to subtract blue light from white light
  In part a., we showed that yellow absorbs or subtracts blue light.
  So a material that subtracts blue light from white light is colored yellow.
  So R + G = Y
- So G + B = White - R
  So to make G + B, we need to subtract red light from white light
  In part a., we showed that cyan absorbs or subtracts red light.
  So a material that subtracts red light from white light is colored cyan.
  So G + B = C
- So B + R = White - G
  So to make B + R, we need to subtract green light from white light
  In part a., we showed that magenta absorbs or subtracts green light.
  So a material that subtracts green light from white light is colored magenta.
  So B + R = M

5. Colors that differ in amount of blue are:

a. Black = No light
   Blue = No light + Blue
b Red = Red
   Magenta = Red + Blue
c. Green = Green
   Cyan = Green + Blue
d. Yellow = Red + Green
   White = Red + Green + Blue

So color combinations that should be avoided are black and blue; red and magenta; green and cyan; yellow and white.

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6. Human visual perception can be thought of as a system of color sensors (hardware) followed by some color processing (software). Try to figure out how the hardware and software works given the following information:

1. Using red, green, and blue lights, we can produce all colors ((Hint: this relates to the hardware)
2. Color blind people are cannot differentiate either reds and greens or yellows and blues. (Hint: software)
3. We do not see reddish greens or yellowish blues.
4. Blue plays no part in our perception of lightness or brightness. (Hint: software)
5. Red light + green light produces the sensation of yellow light. (Hint: software)
6. In the L* a* b* color system, which is based on the human visual system, the positive x-axis refers to redness, the negative x-axis refers to greenness, the positive y-axis refers to yellowness, the negative y-axis refers to blueness, and z axis represents lightness or brightness - from black to white.(Hint: software)

Item 1 tells us that we have red sensors, green sensors, and blue sensors (hardware) also known as our cones.

Item 5 tells us that the output of the red sensor and the green sensor are wired together and their output gives us the sensation of yellow.

Item 3 tells us that the red and the green inputs to the processing are combined in such a way that we can detect either red or green but not both. It also tells us that the yellow and blue inputs to the processing are combined in such a way that we can see yellow or blue but not both.

Item 2 gives us essentially the same information as item 3.

Item 4 tells us that the perception of lightness is due to the red and green sensors only. Since both red and green contribute to our sensation of lightness, the output of the red and green sensor must be combined to give us the sensation of lightness.

Item 6 reinforces items 2-5.

So we can draw the following diagram for our color vision:

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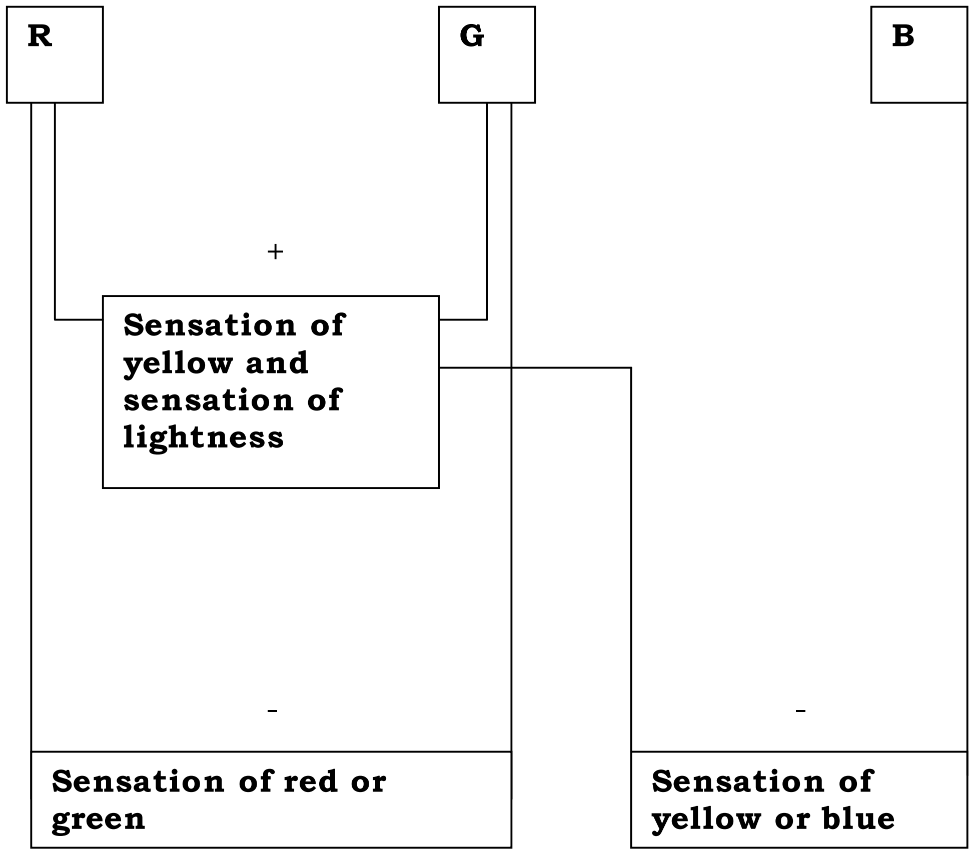

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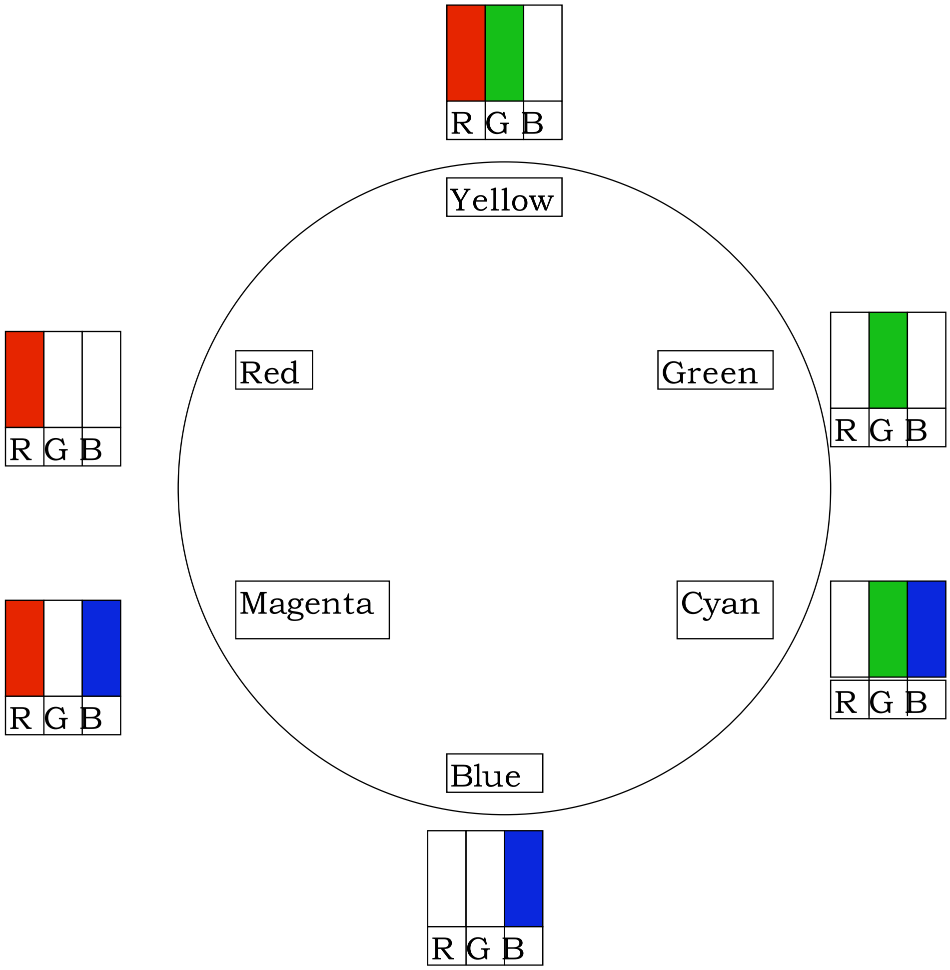

The New Color Wheel

GASEF #011 can be used as a visual aid to help in the understanding of the construction of this color wheel.

Note that that the colors red, yellow, and green contain no blue light in them, whereas magenta and cyan do contain blue light. So the pigment yellow, which absorbs blue light, should be at the 100% level for red, yellow, and green, gradually fading to 0% yellow at magenta and cyan.

Note that that the colors red, magenta, and blue contain no green light in them, whereas yellow and cyan do contain green light. So the pigment magenta, which absorbs green light, should be at the 100% level for red, magenta, and blue, gradually fading to 0% magenta at yellow and cyan.

Note that that the colors green, cyan, and blue contain no red light in them, whereas yellow and magenta do contain red light. So the pigment cyan, which absorbs red light, should be at the 100% level for green, cyan, and blue, gradually fading to 0% cyan at yellow and magenta.

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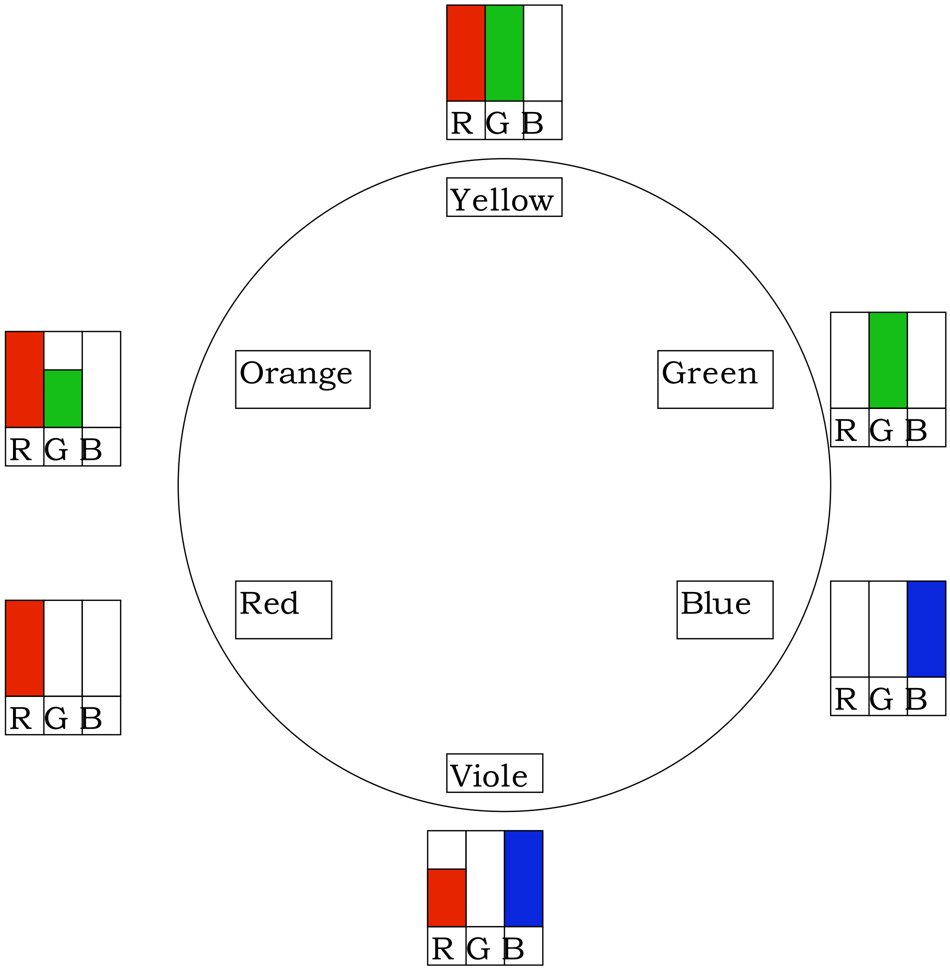

The Traditional Color Wheel

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Appendix 1:
Some Word Fun

As an amateur punster, I decided to make up (or in one case copy) some word games using color words. They are cleverly hidden here in Appendix 1 so that you can easily ignore them if you wish because, as my 11 year old daughter Rachel says, "they're sssoooo stupid." Rachel also gave each word game a rating based on 5 stars, ***** being the best. (Teachers note: subtle integration of science and language arts!)

Word Games

1. Rearrange the letters in COLOR to complete this sentence:

    If you like color, then U _ _ _ _ _! ****1/2

2. Use one of the primary colors to answer this question:

    Are you a color lover? Yes, ________. ****

3. Rearrange the letters in GREENY to complete this sentence:

Tiny weeny greeny plants get _ _ _ _ _ _ from the sun. **1/2

4. Rearrange the letters in MAGENTA to spell the synonym for:

    A. **" a guard at the door of a fence" (1 word)** **

    B. **" a paper that identifies who you are." (2 words)**

5. Rearrange the letters in YELLOW to describe this failing grade that is rarely given:

    _ _ _ _ _ _ *

6. Complete the following sentences using words that sound alike, but are spelled differently (homonyms).

    Don't forget to be _________________ to people who know the correct

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_________________ colors. **

Have you ever ______ a book about the _______ balloon. **

The wind _______ away the ________ folder that held all of my homework. *

7. Complete this sentence (say it as if you were missing your 2 front teeth):

   If you're not wong, then you must be ________. ***

8. **Every letter in this word has a neighbor in the alphabet.** *
   (For example, in the word "tabs," both a and b as well as s and t are neighbors in the alphabet, so every letter in "tabs" has a neighbor in the alphabet.)

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Answers to Word Fun

1. If you like color, then U R COOL!
   (Note that if you spell color the English way - COLOUR - then the appropriate sentence to complete would be:
   If you like colour then U   R   C O O L !)

2. Are you a color lover?   Yes, CYAN. (Yes, I am)

3. Tiny weeny greeny plants get ENERGY from the sun.

4. A. GATEMAN
   B. NAME TAG

5. LOWLY E

6. Don't forget to be COMPLIMENTARY to people who know the correct COMPLEMENTARY colors.

   Have you ever READ a book about the RED   balloon.

   The wind BLEW away the BLUE folder that held all of my homework.

7. If you're not wong, then you must be WHITE.

8. BLACK   (ABC,   KL)

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References

An updated list of the references (web sites, articles, books) is kept at the web site below:

http://www.sci-ed-ga.org/modules/materialscience/color/sites.html

All of the web site references listed in the above web site are hyperlinked.

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<u>Materials List</u>

1. The handheld microscopes, which contain both a 30 x light microscope and an 8 x magnifier, are available from Radio Shack for about $ 8. They are called the Radio Shack 30 x Illuminated Microscope, catalog number 63-851. It requires 2 AA batteries.
Needed for Experiments 1,2,5

2. Rainbows can be projected onto the classroom wall or on a screen using an overhead projector with a slit down the middle of the platen and a diffraction grating.
Sheets of holographic diffraction grating can be purchased from Learning Technologies, Inc. 1-800-537-8703.
Sheets can also be ordered from Edmund Scientific
$10.00 each for a 12 inch x 6 inch sheet Part Number C52,990
Diffraction gratings mounted in 2 inch x 2 inch slides can also be ordered from Edmund Scientific in

Package of 15	Part Number C52,991	$15.95
Package of 25	Part Number C52,992	$24.50
Package of 80	Part Number C52,993	$61.00.

Needed for Optional Procedure in Experiment 2.

3. Transparent films colored red, green, blue, cyan, magenta, and yellow can be purchased from the General Atomics Sciences Education Foundation, item # GASEF 001. Remove the colored films from the plastic cover sheet. Each colored film should be cut into rectangles. Each film should provide enough material for a class of about 30.
Needed for Experiments 2,3.

4. Transparent gradient films can be purchased from the General Atomics Sciences Education Foundation, item # GASEF 005. Remove the colored films from the plastic cover sheet. Cut the gradient color strips into horizontal strips so that they can be slid over one another.
Needed for Experiments 2,3.

5. Large and small diameter color wheels and wheels colored red, green, blue, cyan, magenta, and yellow can be purchased from the General Atomics Sciences Education Foundation, item # GASEF 002 or item # GASEF 003. Remove the colored films from the plastic cover sheets. Cut the 4 color wheels of each sheet of GASEF 002 into 4 smaller separate color wheel sheets, so that they can be overlapped.
Needed for Experiment 6.

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6. The Color Wheel Wall Chart poster can be used as a handy visual guide to the teaching of this unit. It can be purchased from the General Atomics Sciences Education Foundation, item # GASEF 004. A smaller version is available as item # GASEF 007.

Panels 1,2,3 correspond to concepts used in Experiment 1.
Panel 4 corresponds to concepts used in Experiment 2.
Panels 5,6 correspond to concepts used in Experiment 3.

Panel 1	Panel 4
Panel 2	Panel 5
Panel 3	Panel 6

7. Details about the availability of the white LED can be obtained from Tom Baraniak at Baraniak@src.wisc.edu

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Educational Materials

Details, pictures, and information on the use of all of our instructional color materials and posters can be obtained on the following web site:

http://www.sci-ed-ga.org/modules/materialscience/color/materials.html

An order form can be printed out from the following web site:

http://www.sci-ed-ga.org/modules/materialscience/color/orderform.html

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General Atomics Sciences Education Foundation Web Site

Visit http://www.sci-ed-ga.org to obtain:

- Additional information about the General Atomics Sciences Education Foundation
- Additional information about this and other educational modules developed jointly by General Atomics scientists and San Diego area teachers

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