Lab Guide
Color Addition

I. Objectives

After completing this simulation, the student will be able to:
1. Identify the three primary additive colors
2. Identify the complementary color of any of the additive colors
3. Predict the color of the combination of any two additive colors
4. Predict the color of mixing all three additive colors

II. User Interface and Simulation Features

Human color vision is rather complicated and relies on electrical signals produced by nerve cells as a result of both luminous intensity and combinations of wavelengths of light. These electrical signals are mediated by both chemical compounds called "opsins" and relationships between different kinds of neurons. This simulation allows you to add light of three different colors but of equal intensities. Each color of light is represented by a light bulb that you turn on or off by clicking on it. The color appears as a circular area of light of the color you chose. The colored areas can be moved by clicking and dragging them. By superimposing two or three colored areas, you can describe how the human eye perceives these combinations of colors.

III. Questions

In each case when you start a simulation for the following questions, reset the values using the icon in the control panel at the left side of the screen. Each question assumes that you have done this. Then set only the values indicated in the question.

<u>a. Introductory Level</u>

1. Turn on the green and blue lamps by clicking on them. Drag the blue light over the green light. What color is produced by mixing these two colors?

2. Turn on the green and red lamps. Drag the red light over the green light. What color is produced by mixing these two colors?

3. Turn on the red and blue lamps. Drag the red light over the blue light. What color is produced by mixing these two colors?

<u>b. Intermediate Level</u>

4. What is the color that is complementary to the color produced in Item 1?

5. What is the color that is complementary to the color produced in Item 2?

6. What is the color that is complementary to the color produced in Item 3?

c. Advanced Level

7. Turn on all three lamps. Drag the red light partly over the blue light. Drag the green light and drop it so that it partly covers the intersection of the red and blue lights. Mixing all three primary additive colors produces what color?

8. Suppose this simulation was actually performed in the laboratory. In order to produce the results that you observed, what color must the screen be on which these colors are projected? Comment on the necessary conditions of the surroundings of the apparatus.

Lab Guide
Color Subtraction

I. Objectives

After completing this simulation, the student will be able to:
1. Identify the three primary subtractive colors
2. Identify the complementary color of any of the subtractive colors
3. Predict the additive color transmitted by a combination of any two subtractive colors
4. Predict the result of combining all three subtractive colors

II. User Interface and Simulation Features

This simulation allows you to subtract colors of light from white light. Physically, this can be done using transparent color filters of plastic or glass, or certain kinds of ink applied to paper. In this simulation we use markers to apply ink. This ink will transmit, or allow certain colors of light to pass through the ink. Click on a marker to create a circle of ink. You can drag and drop the circles of ink over one another to see the effect of a combination of subtractive colors. By superimposing two or three colored areas, you can describe how the human eye perceives the subtraction of these combinations of colors.

III. Questions

In each case when you start a simulation for the following questions, reset the values using the icon in the control panel at the left side of the screen. Each question assumes that you have done this. Then set only the values indicated in the question.

<u>a. Introductory Level</u>

1. Click on the magenta and yellow markers. Drag the magenta ink over the yellow ink. What two additive colors allow you to see magenta when they are combined? These are the two colors that will be transmitted by the magenta ink. What two additive colors allow you to see yellow? Yellow will transmit only these colors. Which color will both subtractive colors transmit? Which additive color does the simulation show?

2. Click on the magenta and cyan markers. Drag the magenta ink over the cyan ink. What primary additive colors are transmitted by the magenta ink? What primary additive colors are transmitted by the yellow ink? Which color will both subtractive colors transmit? Which additive color does the simulation show?

3. Click on the yellow and cyan markers. Drag the yellow ink over the cyan ink. What primary additive colors are transmitted by the yellow ink? What primary additive colors are transmitted by the cyan ink? Which color will both subtractive colors transmit? Which additive color does the simulation show?

Intermediate Level

4. Superimpose all three subtractive colors on the screen. The complementary additive color appears across from each subtractive color. What is the complementary color to magenta?

5. What is the complementary color to cyan? Superimpose all three subtractive colors on the screen to check your answer

6. What is the complementary color to yellow? Superimpose all three subtractive colors on the screen to check your answer

c. Advanced Level

7. What remains if you all view all three subtractive colors together? Why is this so?

8. What color must the background, or screen, be to account for what you observe in this simulation?

Lab Guide
Simple Lens

I. Objectives

After completing this simulation, the student will be able to:
1. Estimate the position of an image, given information about the lens and the object
2. Explain the meaning of "focal length"
3. Explain the meaning of "magnification"
4. Compare and contrast converging and diverging lenses
5. Compare and contrast real and virtual images

II. User Interface and Simulation Features

In this simulation you form and image of an object and explore how changing different variables affects the size and position of the image. The simulation uses two main formulas. The first is the thin-lens formula $\frac{1}{i}+\frac{1}{o}+\frac{1}{f}$ where i, o, and f represent the object distance, image distance and focal length, respectively. The other is the magnification formula $M=\frac{h_i}{h_o}=\frac{-i}{o}$ where h_i and h_o are the heights of the image and the object, respectively. A bright blue bar represents the object. A bright green bar represents the image of that object. One end of the bar is always on the principal axis. You can drag the other end of the blue bar to change the size of the object. You can drag the ⊕ on the blue bar to change its position on the principal axis. The size and position of the image are determined by those of the object and cannot be set independently. The size and distance from the lens for both object and image are displayed at the top of the screen. A grid may be turned on and off. The grid has a scale of 2 cm/division. The position of the lens can be moved left and right. Small purple dots represent the focal length on both sides of the lens. The focal length of the lens can be changed by means of the slider bar. When the focal length becomes negative, the lens becomes a diverging lens. Red lines indicate the most common rays used for the ray-tracing technique. The image is located at the point where the rays intersect. When the rays turn a bright green, it means that the image is virtual.

III. Questions

In each case when you start a simulation for the following questions, reset the values using the icon in the control panel at the left side of the screen. Each question assumes that you have done this. Then set only the values indicated in the question.

<u>a. Introductory Level</u>

1. The simulation defaults to a converging lens. Is the image larger or smaller than the object? Is the image closer or farther away from the lens than the object? Is the image real or virtual? Is the image upright or inverted?

2. What happens to the image size as you move the object away from the lens? How does the image distance change? How does the distance between the image and the focal point change?

3. Set the focal length to 10 cm. Gradually move the object left to $o = 20\ \text{cm}$. What is the object height? What happened to the image distance and size?

4. Move the lens so that it is a distance of about twice the focal length from the right side of the grid. Move the object so that it is just to the left of the focal point on the left side. What happened to the image as you moved the object? Now move the object slowly all the way to the left of the grid. What happens to the image? If you moved the object an infinite distance away from the lens, where would its image be located?

b. Intermediate Level

5. Slowly move the object closer to the focal point. What happens to the image? What happens when the object is located exactly at the focal point? Where is the image?

6. Move the object just inside the focal point. What has happened to the rays? Is the image behind the lens or in front of the lens? Is it virtual or real? Is the image upright or inverted? Accept the default focal point of 5.5 cm. Move the object to 4.0 cm from the lens. Use the thin lens formula to calculate the position of the image. What value do you obtain? What value does the simulation report?

7. Change the focal length to $f = -5.0\ \text{cm}$. Move the object farther from and closer to the lens. What happens to the image height? What are the limits on the image location? Is the image real or virtual? Is it upright or inverted? Can you ever obtain a real image with a diverging lens? Is the image ever larger than the object?

8. Where would a simple lens form an image of a star?

c. Advanced Level

9. The simplest refracting telescope consists of two lenses. The front lens forms a real image at some point between the two lenses. The eyepiece, or ocular, in turn uses this real image as its object, and forms a virtual image of this primary real image. It is the virtual image that you see when you look into the eyepiece. Would you expect the image that you see to be inverted or upright? If you were observing stars at night and then wanted to look at a bird in a nearby tree the next day, would you move the eyepiece closer to or farther away from the front lens in order to focus on the bird?

10. The formula in the User Interface and Simulation Features is called the "thin lens formula" because it gives very close approximations when the thickness of the lens is very small compared to the focal length and object and image distances. What would happen to the rays and image position if the lens were rather thick?

11. Repeat Item 6 and calculate the magnification using the formula given in User Interface and Simulation Features. What value do you get? Observe the relative height and orientation of the object and image. Note the sign of the magnification and whether its absolute value is greater than or less than one. Now set the object distance to $o = 4.0\ \text{cm}$. Calculate the magnification. What value do you obtain? Observe the relative height and orientation of the image and object. What significance does the sign of M have? Of what significance is the magnitude of M compared to unity?

Lab Guide
Fermat's Principle

I. Objectives

After completing this simulation, the student will be able to:
1. Dynamically locate minimum values on a graph
2. Explain refractive index in terms of Fermat's Principle
3. Calculate distance relationships using the Pythagorean Theorem and trigonometry
4. Compare time-of-travel using velocity and distance data.

II. User Interface and Simulation Features

The point of this simulation is to find the minimum time of travel for a signal traveling through two different media. The signal may have different speeds in each of the media.. Fermat's principle states that light will take the path of least time compared to nearby paths. This is true when a ray of light moves from a medium with a given refractive index to a medium with a different refractive index. The starting and ending points are shown as "dish antennae" to the left and right of the screen, with a planet in between. Think of this as the antenna on the left sending a signal to a station on the planet. The station then relays, without delay, the signal to the antenna on the right. The location of the planet defaults to a point on the boundary between two media. You can drag the planet to a desired location within the center part of the grid. To keep the planet on the line between the media, hold down the <shift> key You are able to vary the speed of the signal in both media. The grid spacing is 10 m per division. If you change the speed of the signal using the slider bars at the bottom of the screen, the time display will not change until you move the planet in an attempt to find the new least time path.

III. Questions

In each case when you start a simulation for the following questions, reset the values using the icon in the control panel at the left side of the screen. Each question assumes that you have done this. Then set only the values indicated in the question.

<u>a. Introductory Level</u>

1. Using the default values, hold the <shift> key down and move the planet up and down the dividing line between the media until you obtain a minimum value for time in seconds. What is this value?

2. Turn the "Grid Snap" off. Without this constraint, hold the <shift> key down and move the planet up and down the dividing line between the media until you obtain a minimum value for time in seconds. Is there a difference in the minimum value for time with and without this constraint?

3. Move the left antenna to the far upper left of the grid. Move the right antenna to the far lower right of the grid. Set the velocity in the left medium to $v_1 = 1.0 \text{ m/s}$. Set the velocity in the right medium to $v_2 = 5.0 \text{ m/s}$. Hold the <shift> key down and move the planet to find the path of least

time? What is the time value? Now turn the "Grid Snap" off. Can you find a lower least time path between scale divisions? What is the time value?

b. Intermediate Level

4. Move the left antenna to the far upper left of the grid. Move the right antenna to the far lower right of the grid. Set the velocity in the left medium to $v_1 = 1.0\ \mathrm{m/s}$. Set the velocity in the right medium to $v_2 = 5.0\,\mathrm{m/s}$. Do not hold the <shift> key down. Move the planet to find the path of least time. Try to find a least time path off the dividing line between the media. Is there such a path? Be sure to check in the immediate area by moving the planet a bit diagonally as well as vertically and horizontally. What is the time value? Now turn the "Grid Snap" off. Can you find a lower least time path between scale divisions? What is the time value?

5. Move the left antenna to the far upper left of the grid. Move the right antenna to the far lower right of the grid. Turn off the "Grid Snap." Set the velocity in the left medium to $v_1 = 2.0\ \mathrm{m/s}$. Set the velocity in the right medium to $v_2 = 4.5\,\mathrm{m/s}$. Move the planet to find the path of least time. What is the time value? Look at the two angles, θ_1 and θ_2. Is there a relationship between velocity in a medium and the angle at which the signal approaches or leaves the medium? Verify this by repeating with different values for v_1 and v_2. Does this relationship still hold?

6. Move the left antenna to the far upper left of the grid. Move the right antenna to the far lower right of the grid. Turn off the "Grid Snap." Set the velocity in the left medium to $v_1 = 2.0\ \mathrm{m/s}$. Set the velocity in the right medium also to $v_2 = 2.0\,\mathrm{m/s}$. Move the planet to find the path of least time. What is the time value? Look at the two angles, θ_1 and θ_2. What do you observe? Why do you think this is so?

7. Center the planet at the origin of the grid. Place the left antenna on the x-axis at the far left. Place the right antenna on the x-axis at the far right. Set $v_1 = 3.5\,\mathrm{m/s}$ and $v_2 = 3.0\,\mathrm{m/s}$. What is the time value? Is the x-axis a path of least time? How can this be so, considering what you observed in Items 5 and 6?

c. Advanced Level

8. Move the left antenna to the far upper left of the grid. Move the right antenna to the far lower right of the grid. Turn off the "Grid Snap." Set the velocity in the left medium to $v_1 = 2.0\ \mathrm{m/s}$. Set the velocity in the right medium to $v_2 = 4.5\,\mathrm{m/s}$. Move the planet to find the path of least time. Consider both the time in each region and the velocity in that region. In which medium did the signal travel farthest? In which medium did the signal spend the most time? Calculate the distance traveled in each medium.

Lab Guide
Basic Prism

I. Objectives

After completing this simulation, the student will be able to:
1. State whether longer wavelengths are refracted more or less than shorter wavelengths.
2. Define refractive index
3. Compare angles of incidence and angles of refraction for prisms.
4. Use Snell's law to calculate index of refraction, given the index of refraction for air.
5. Describe the dispersion of white light by a prism

II. User Interface and Simulation Features

To change the wavelength of light entering the prism, click and drag the hand pointing to the spectrum on the laser. To see the effect of refraction on white light, click and hold on the button so labeled. The spoked wheels are protractors marked off in 15° increments. They are useful in estimating the angles of incidence and refraction. They are oriented so that one aligns with the first surface and the other aligns with the second surface. The four angles are also displayed digitally. In the upper center of the screen. The angles θ_1 and θ_2 represent the angle between the ray of light and a line normal to the face of the prism for the incident ray as it enters the prism (a normal line looks perpendicular in a two-dimensional display). The angles θ_3 and θ_4 represent the same angles for the refracted ray as it leaves the prism.

III. Questions

In each case when you start a simulation for the following questions, reset the values using the icon in the control panel at the left side of the screen. Each question assumes that you have done this. Then set only the values indicated in the question.

<u>a. Introductory Level</u>

1. Observe the simulation with default values. What is the angle of incidence for the first surface? What is the angle of incidence for the second surface? What wavelength of light is being used? What color does it appear to be?

2. Observe the simulation with default values. What is the angle of refraction for the first surface? What is the angle of refraction for the second surface?

3. Consider the default settings. What change in wavelength is needed to reduce the angle of refraction θ_2 by 1.0°?

4. What happens to the angle of incidence at the second surface, θ_3, when you change the wavelength from 700 nm to 620 nm? From plane geometry, is this logical?

b. Intermediate Level

5. What happens to white light after it strikes a prism? Describe the effects at both first and second surfaces.

6. Define index of refraction, n.

7. With the glass used in this simulation, what is the maximum change in angle of refraction θ_4 with wavelength over the range of the spectrum provided in the simulation?

c. Advanced Level

8. Set the wavelength to 560 nm. Air has an index of refraction $n = 1.00$. Using the angles at the first surface, what value do you obtain when you calculate the index of refraction of the glass of the prism? Now check your work by using the angles at the second surface. What value do you obtain there? How does this compare with the graph in the Theory section?

Lab Guide
Snell's Law

I. Objectives

After completing this simulation, the student will be able to:
1. State Snell's Law
2. Explain total internal reflection
3. Define critical angle
4. Demonstrate total internal reflection in the simulation
5. Show the effect of wavelength on critical angle

II. User Interface and Simulation Features

The simulation consists of a laser light source of variable wavelength and a semi-cylindrical plate of glass attached to a goniometer. This device measures the angle of the light beam with respect to the normal line. You can change the refractive index of the glass and the wavelength of the light from the laser using the slider bars at the bottom of the screen. A histogram at the upper left shows the index of refraction, the wavelength of the light, the angle of incidence and the angle of refraction.

III. Questions

In each case when you start a simulation for the following questions, reset the values using the icon in the control panel at the left side of the screen. Each question assumes that you have done this. Then set only the values indicated in the question.

<u>a. Introductory Level</u>

1. Set the refractive index of the glass to $n = 1.0$. This is the same value as for air. Move the plate angle slider through its full range and back. Does the light beam refract?

2. Accept the default values. Move the plate angle slider from 0° to 90°. Does the light beam always both enter and exit the glass in this range of angle? Is there a place where the light is reflected from the flat surface of the glass?

3. Accept the default values. Move the plate angle slider from 270° to 359°. Does the light beam always both enter and exit the glass in this range of angle? Is there a place where the light is reflected from the flat surface of the glass?

<u>b. Intermediate Level</u>

4. Set the plate angle slider to 180°. This is the angle of the normal line. Slowly change the angle of the light beam down to 90°. Did the path of the light beam change from being refracted to being reflected? At how many degrees away from the normal did it happen? Now change the angle slowly from 180° to 270°. What do you observe? At how many degrees away from the normal did this happen? This angular displacement from the normal is called the critical angle.

5. Repeat Item 4 for a wavelength of $\lambda = 450\ \mathrm{nm}$. What value do you obtain for the critical angle? Does the value of the critical angle depend on the wavelength?

6. The spectrophotometric reagent known as FerroZine combines with iron to produce a purple color. Produce a light beam of $\lambda = 560\ \mathrm{nm}$ where the FerroZine-iron complex absorbs light. Set the refractive index to $n = 1.63$, that of silicate flint glass. What is the range of angle of incidence that produces total internal reflection?

c. Advanced Level

7. Produce a light beam of $\lambda = 590\ \mathrm{nm}$, close to the sodium doublet. Set the refractive index to $n = 1.33$, simulating an air-water interface. Set the angle of incidence to 45°. Air has a refractive index of $n = 1.00$. If the light propagates in air, then the angle of incidence is in air and the angle of refraction is in water. What is the sine of the angle of incidence? What angle of refraction do you observe? What is its sine? What is the ratio of the sines of the two angles? Snell's law relates the ratio of the sines of the two angles to the ratio of the refractive indices. Exactly how does Snell's law relate them?

8. Set the refractive index to 1.52, about that of silicate crown glass. Set the wavelength to $\lambda = 500\ \mathrm{nm}$, about that of an argon laser used for eye surgery. Set the angle of incidence to $\theta_{in} = 40.0°$. Calculate the angle of refraction using Snell's Law. Compare your value with that reported by the simulation.

Lab Guide
Polarization

I. Objectives

After completing this simulation, the student will be able to:
1. Describe the operation of polarizing and analyzing filers
2. Qualitatively describe polarized light
3. Describe the effect of multiple polarizers

II. User Interface and Simulation Features

This simulation consists of a light box as a light source. The intensity of the light from the box is $1.000\,\mathrm{W/m^2}$ This light can be changed from unpolarized to vertically polarized. The light box has two polarizing filters on it. Each filter can be rotated through an angle of 180°. Each filter can be dragged and dropped to a desired location on the light box. The filters can be superimposed in order to experiment with multiple polarizers. You can choose to show the polarization axes. The intensity of the transmitted light at the position of the cursor is shown in the display at the upper right.

III. Questions

In each case when you start a simulation for the following questions, reset the values using the icon in the control panel at the left side of the screen. Each question assumes that you have done this. Then set only the values indicated in the question.

<u>a. Introductory Level</u>

1. Using the cursor and the intensity display, find the light intensity of the light box. What is the intensity of the light passing through one polarizer? What is the intensity of the light passing through both polarizers?

2. Separate the polarizers by dragging them apart. Rotate the red polarizer. Check the intensity of the light being transmitted. Does the intensity change? Do the same with the blue polarizer. Do you always obtain the same intensity?

3. Drag the blue polarizer over the red polarizer so that they overlap. Set the polarization angle of the red polarizer to $\theta_1 = 0^\circ$. Now rotate the blue polarizer slowly. What do you observe?

4. Drag the blue polarizer over the red polarizer so that they overlap. Set the polarization angle of the red polarizer to $\theta_1 = 0^\circ$. Rotate the blue polarizer. At what angle of the blue polarizer do you observe the least transmitted light? Use the cursor and the intensity display to help you check. What is the difference of the two angles?

5. Drag the blue polarizer over the red polarizer so that they overlap. Set the polarization angle of the red polarizer to $\theta_1 = 45°$. Rotate the blue polarizer. At what angle of the blue polarizer do you observe the least transmitted light? What is the difference of the two angles?

b. Intermediate Level

6. Set the light box to produce vertically polarized light. Rotate the red polarizer so that it transmits the maximum light intensity possible. What is this intensity?

7. Set the light box to produce vertically polarized light. Rotate the red polarizer to an angle of 45°. Using the cursor, what is the intensity of the light transmitted through the red polarizer? Rotate the blue polarizer to an angle of 135°. What is the intensity of the light transmitted through the blue polarizer? What is the intensity of the light transmitted by the combination of both polarizers? Why is this so?

8. When a second polarizer is used to check the angle of polarization of light transmitted by some polarizing material for which the polarizing angle is not known, the second polarizer is called an "analyzer." In this simulation, the angles are known, but we can show the process of analyzing the angle of original polarization. Set the light box to emit unpolarized light. Set the red polarizer to 27°. Rotate the blue "analyzer" until no light is transmitted, using the cursor and intensity display as a guide. What is the angle of the analyzer? Now subtract the value of 90° from the angle of the analyzer. What value do you obtain? Check your work by turning on the polarization axes and observing that they are at right angles.

9. Malus's law states that for incident polarized light of intensity I_0, transmitted intensity I is related to the angle of the analyzer by $I = I_0 \cos^2\theta = I_0 \left(\cos\theta\right)^2$. Set the light box to emit vertically polarized light. Does the light transmitted by the red polarizer obey Malus's law? Now change the angle of the red polarizer to 60°. What is the Intensity of the transmitted light? What does Malus's law predict?

c. Advanced Level

10. Drag the two polarizers apart so they do not overlap. Set the light box to emit polarized light. Set the blue polarizer to 90°. What is the light intensity transmitted by the blue polarizer? Now set the red polarizer to 60°. Drag the red polarizer so that it slides behind the blue polarizer. How did the visual appearance of the overlap area change? What is the measured value of the light intensity of the overlap area? Can you explain this in terms of Malus's law?