

# It's a Colorful Life

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# Why Learn about Color and Color Vision in a Physics Class?

"There are many interesting phenomena associated with vision which involve a mixture of physical phenomena and physiological processes, and the full appreciation of natural phenomena, as we see them, must go beyond physics in the usual sense. We make no apologies for making these excursions into other fields, because the separation of fields, as we have emphasized, is merely a human convenience, and an unnatural thing. Nature is not interested in our separations, and many of the interesting phenomena bridge the gap between fields."

Feynman Lectures on Physics, Volume 1, Chapter 35 (Color Vision)



# Why study color?

- Most interesting new physics and technology is multidisciplinary and interdisciplinary
  - Color is a model system
- Note the variety of models and methods we will use to explore color



# Color: An Ideal System for Using and Understanding Models

- Wide Variety of Different Color Models: inter-related
  - Color math - addition/subtraction/algebra/multiplication/fractions
  - RGB color space - color monitors
  - CMY color space - color printing
  - L\*a\*b\* color space - most common in technology-color distance
  - CIE xyY chromaticity diagram - color science
  - Color wheel - art-but artists color wheel is incorrect
  - Color cube - both RGB and CMY
- Models relate theory and experiment; predict or explain



# Color: a Physics Topic for Everyone

- Good physics
- Relevant to most students
- Enrich a student's life
- Reinforced on a frequent basis in a typical student's life
- Impact the student a year from now



## Color Quiz:

Are these topics appropriate for a physics class?  
Would students find these questions interesting?

1. Why is the sky blue?
2. Why is water blue?
3. Why is water clear?
4. Why are clouds white?
5. How do color printers produce their colors?
6. Why are the primary colors that artists use red, yellow, and blue?
7. Why are fog lights yellow?
8. Why is ice clear?
9. Why is ice cloudy?
10. Why is ice blue?
11. How does a computer screen produce colors?



# Education: Wide or Deep?

- I suggest we want a comb approach



- Some very deep investigations and understanding
- Also general awareness of many topics, but not necessarily detailed understanding
  - So that we can say, I think I remember reading about this or I think ... and then we can investigate further
- This presentation includes in-depth investigations and topics for “awareness”



What do you or your students  
know about color?



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# Introduction-Color Confusion

- Primary colors are R, Y, B
- Primary colors are R, G, B
- Primary colors are C, M, Y
- Colors in rainbow: ROY G. BIV
- Increasing temperature: ROYWB



# How we see color

Basic simplifying assumption:

The color we see results from light of that color entering our eye.



# White Light Experiment

- Place C film over color wheel on W paper
  - C film absorbs what color of light?
- Place M film over color wheel on W paper
  - M film absorbs what color of light?
- Place Y film over color wheel on W paper
  - Y film absorbs what color of light?
- Place C, M, Y films on top of each other
  - What happens? What does this mean?



# White Light Experiment

- Place C film over color wheel on W paper
  - C film absorbs R light ( $W-R=C$ )
- Place M film over color wheel on W paper
  - M film absorbs G light ( $W-G=M$ )
- Place Y film over color wheel on W paper
  - Y film absorbs B light ( $W-B=Y$ )
- Place C, M, Y films on top of each other
  - White light is completely absorbed by the R light absorber, G light absorber, and B light absorber
  - **So white light:  $W=R+G+B$**

*(Letters refer to color of light)*

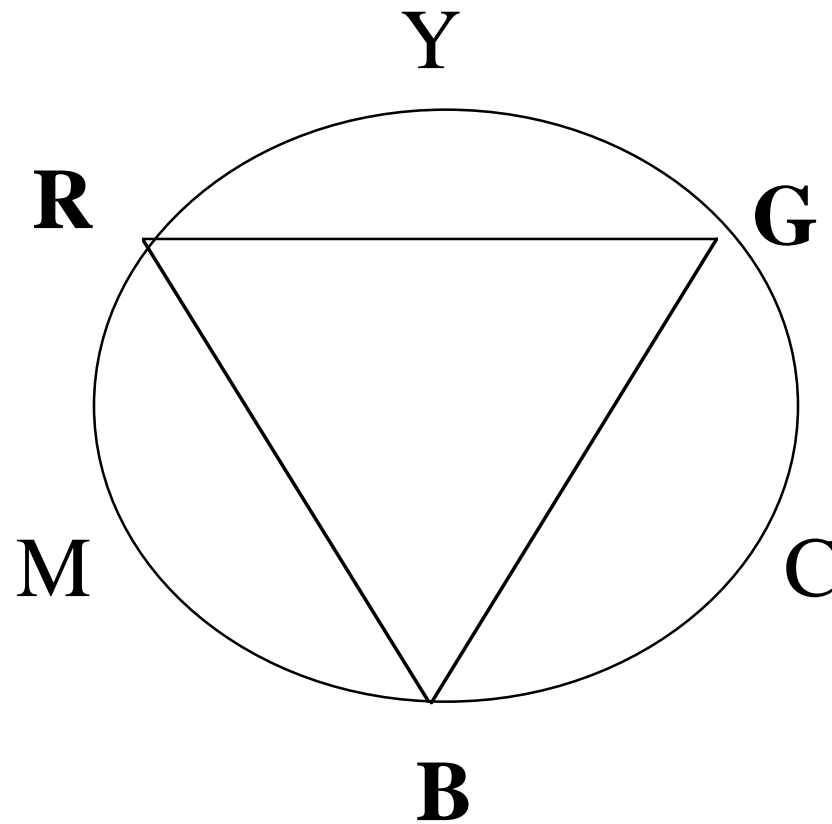


# Use Color Math to Determine Rules for Additive Color Mixing

- We determined that:  $W = R + G + B$
- Therefore:
  - $R + G = W - B = Y$ 
    - Blue absorber appears yellow in white light
  - $G + B = W - R = C$ 
    - Red absorber appears cyan in white light
  - $B + R = W - G = M$ 
    - Green absorber appears magenta in white light
- Use these relations to generate a color wheel



# Color Wheel Model for Additive Colors (Light)



# Complementary Colors of Light

- Overlapping complementary colors of light produce white
- Use color math to show this:
  - C, R :  $C+R = B+G+R = W$
  - M, G:  $M+G = R+B+G = W$
  - Y, B:  $Y+B = R+G+B = W$
- Complementary colors lie on opposite sides of the color wheel

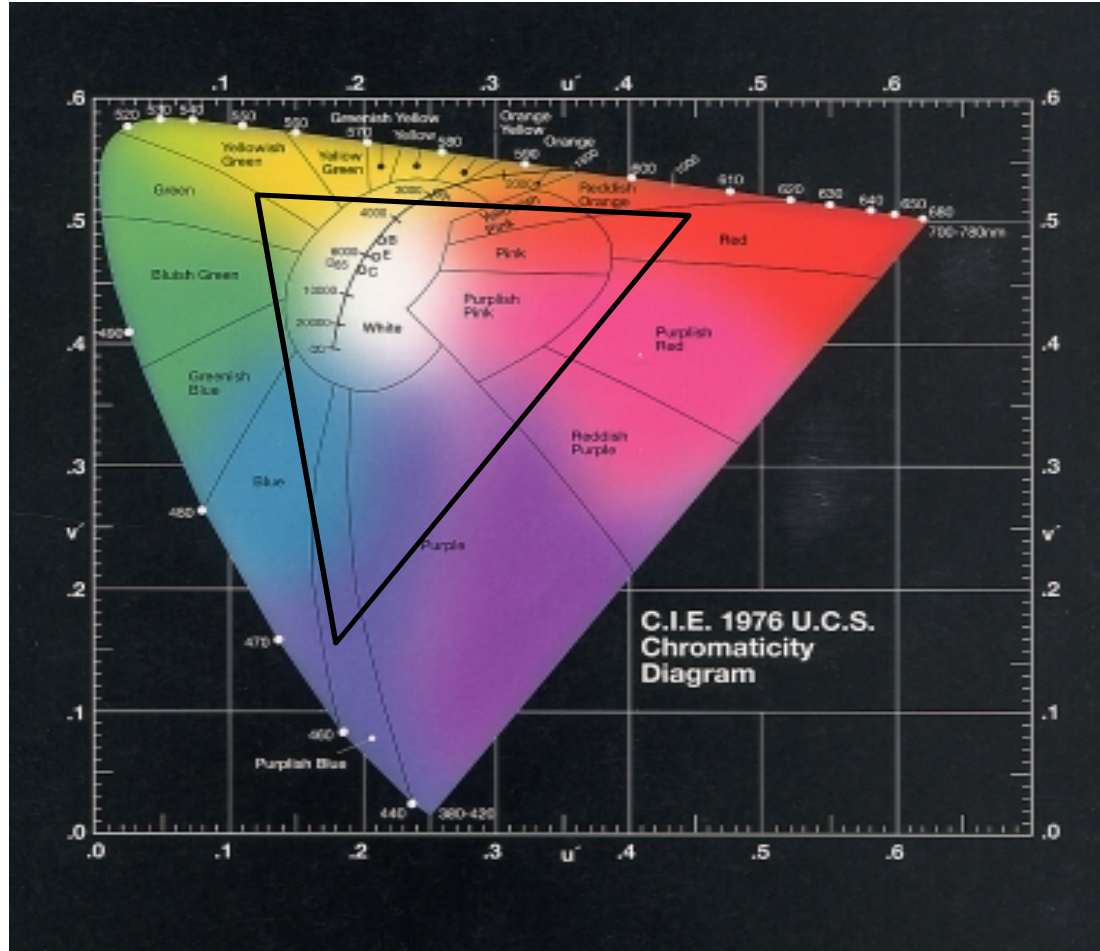


# Primary colors of light

- Combining the 3 primary colors of light produces the largest range of colors of light compared to any 3 other colors.
- We showed that combining R, G, B light produced the distinctly different C, M, and Y light colors.
- It is an experimental fact that red, green, and blue light sources yields the largest range of colors of light.
- So red, green, and blue are the primary colors of light.





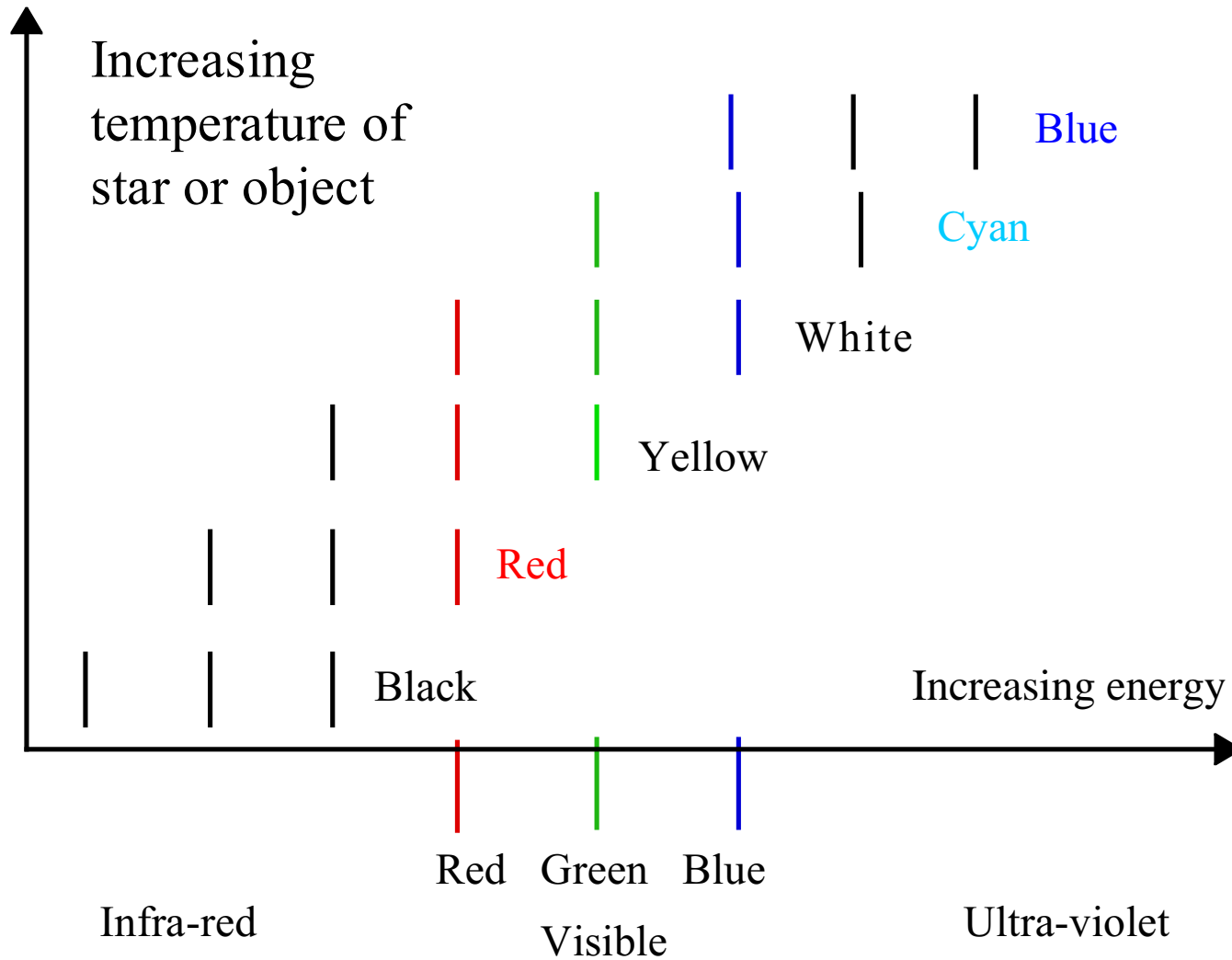


# Other Ways to Explore Additive Color Mixing (Mixing Colors of Light)

- 3 slide projectors: R, G, B (typical)
- 2 slide projectors - better!
  - RG, GB, BR, then RC, GM, BY
- Observe colors on monitor with 8x magnifier (try)
- RGB LED light mixer
- Simulation using RGB model (demonstrate)
- Simulation using RGB model web applet
- **Use color wheel and transparencies (done)**

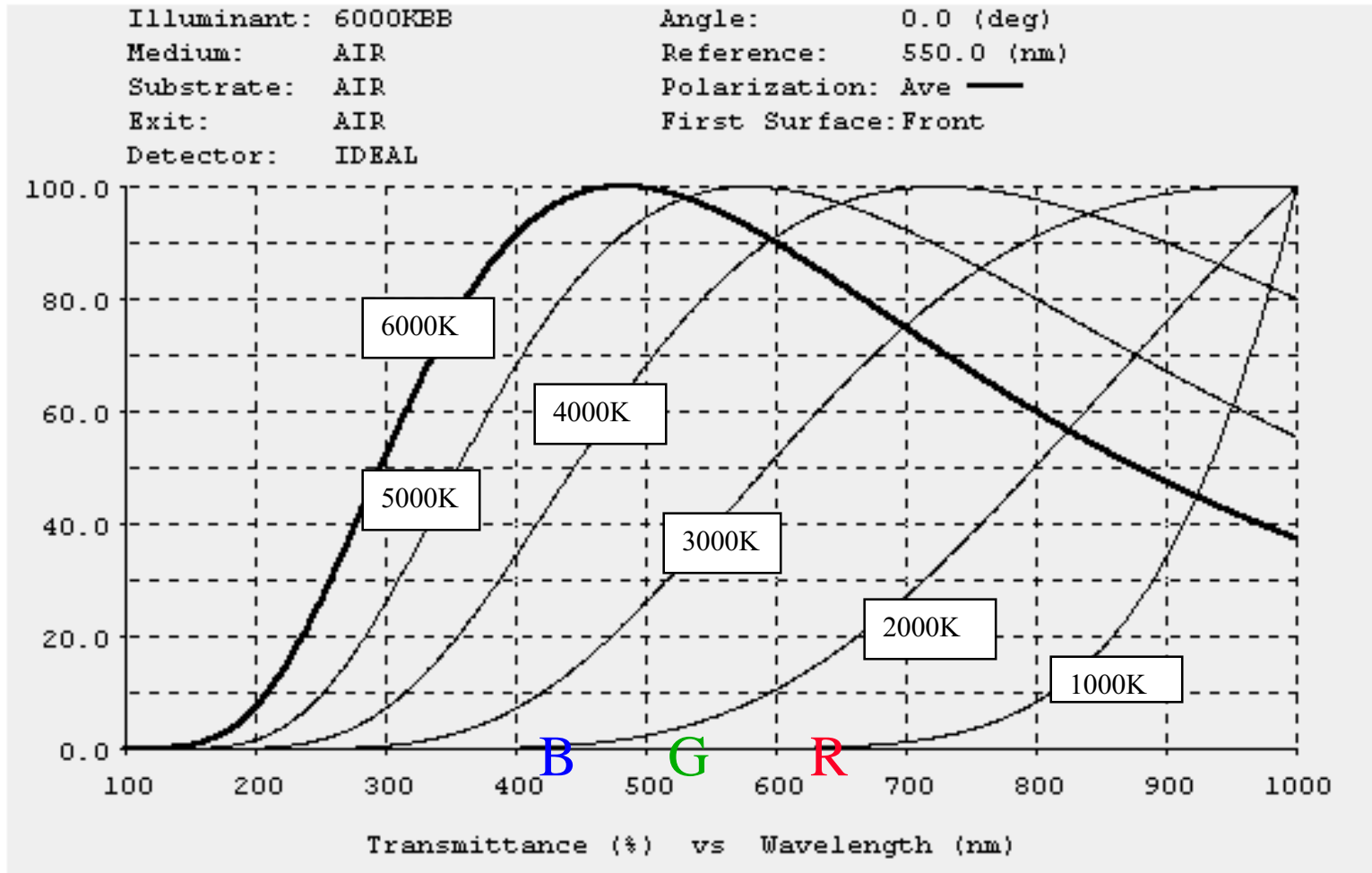


# Application of additive color mixing



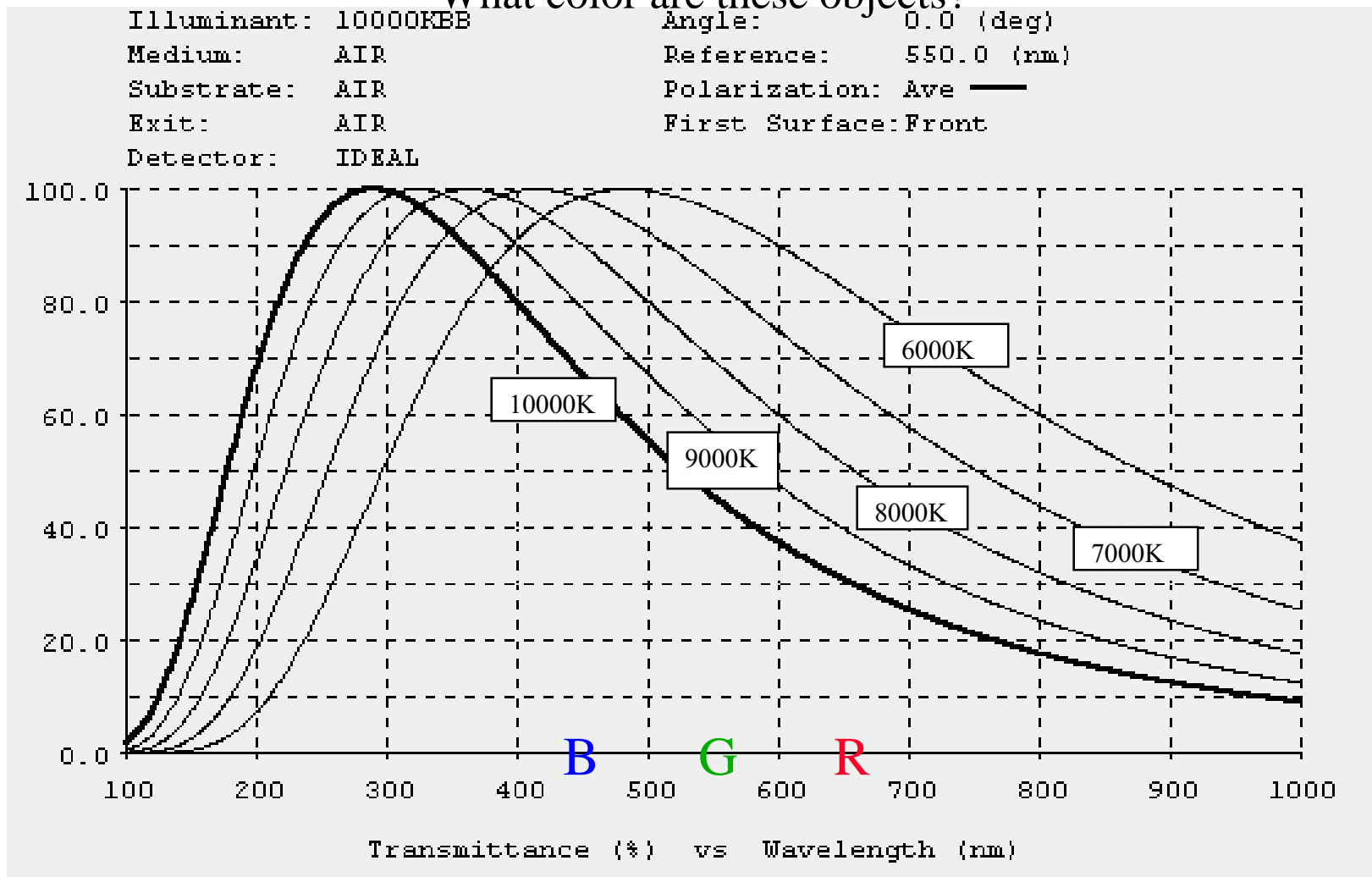
# Normalized blackbody curves – Light intensity vs wavelength

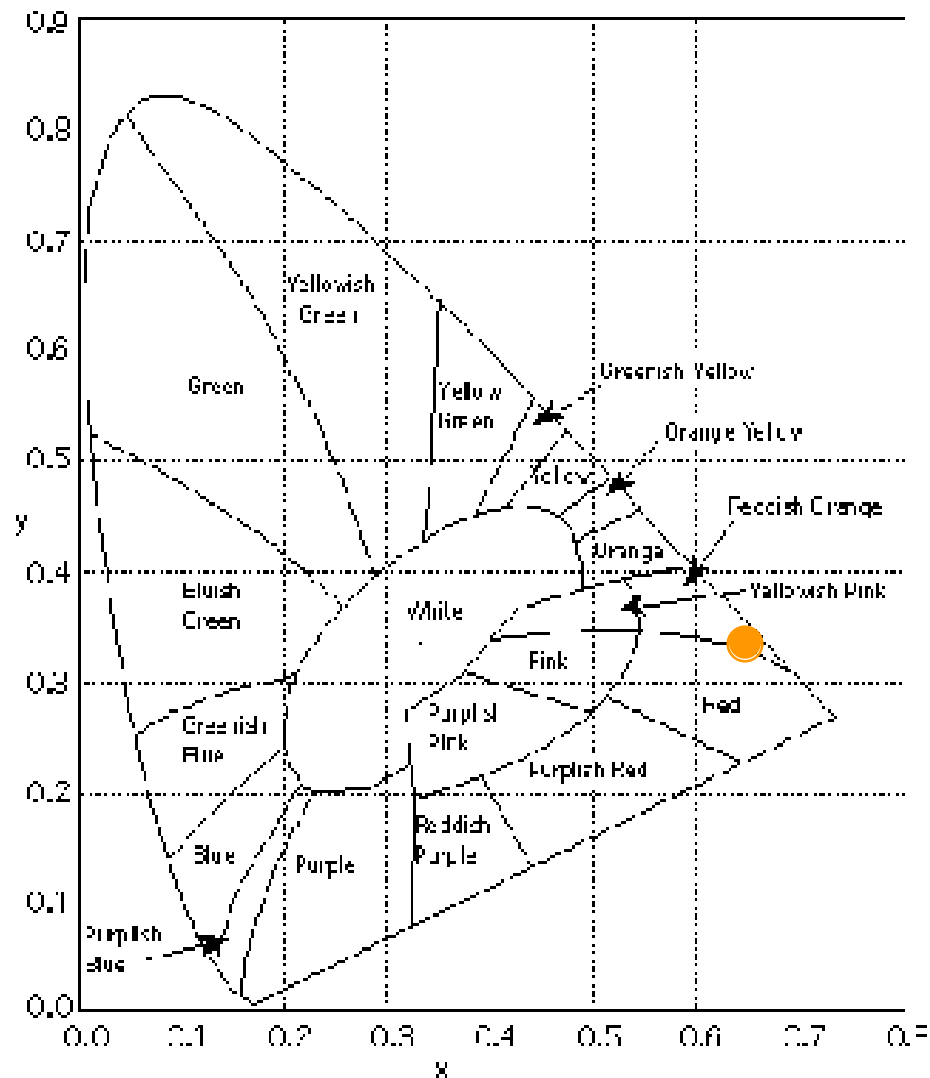
What color are these objects?



# Normalized blackbody curves – Light intensity vs wavelength

What color are these objects?

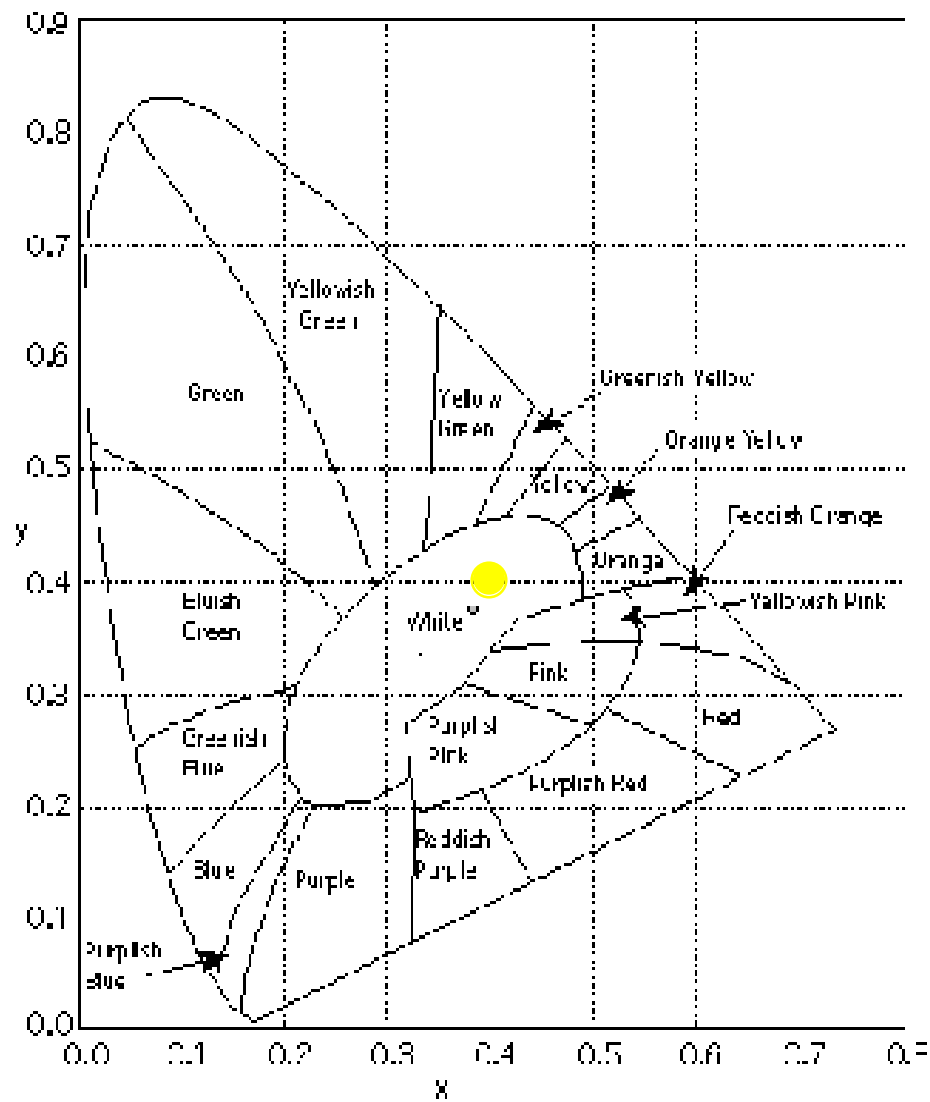




Color Standards: 1901 D1E  
 Field of View: 2°  
 Polarization: Average  
 Reference White: CIE-C  
 Illuminant: 100CIE  
 Incident angle (deg): 0.00

Trans: 100.00  
 x Coordinates: 0.653  
 y Coordinates: 0.345  
 Luminosity (%): 100.00  
 Dominant (nm): 607  
 Complementary (nm): 490  
 Excitation Purity: 0.993

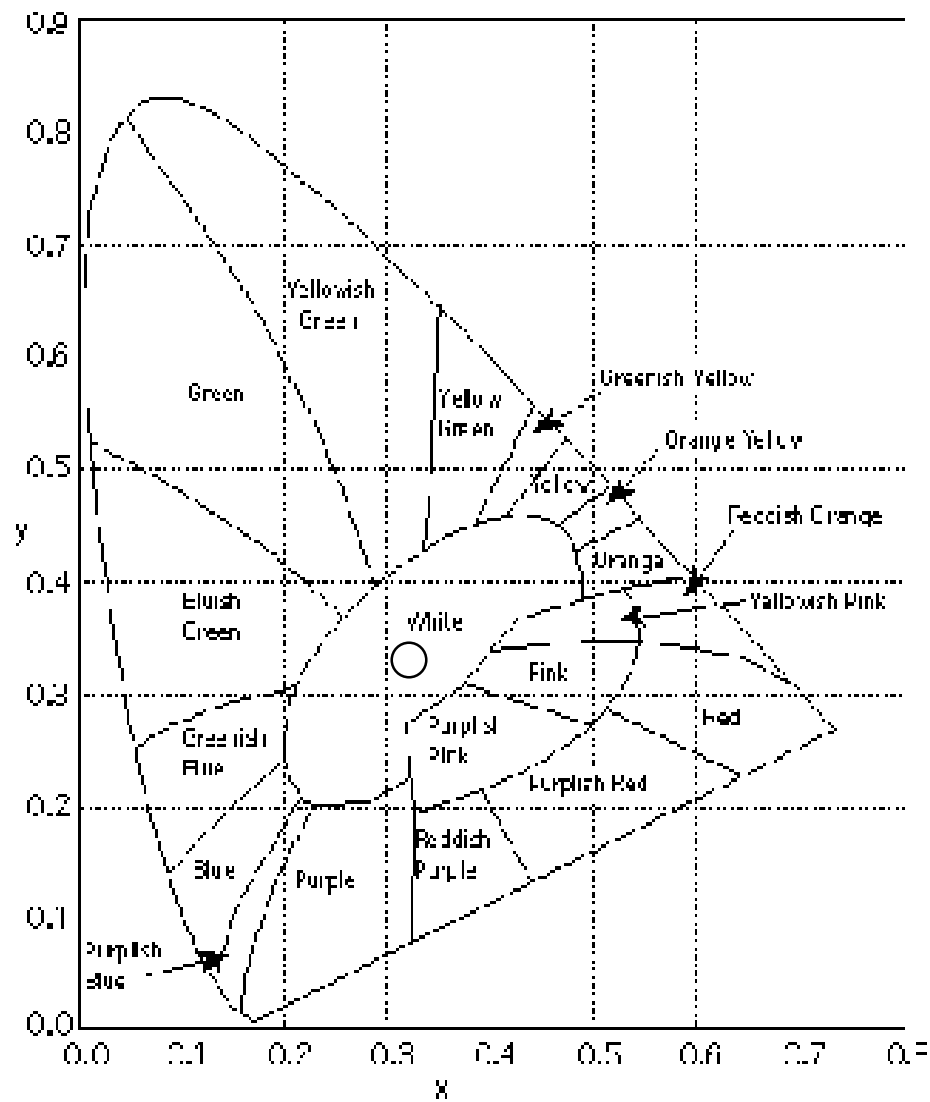




Color Standard: 1931 CIE  
 Field of View: 2°  
 Polarization: Average  
 Reference White: CIE-C  
 Illuminant: 4000KBE  
 Incident angle (deg): 0.00

Trans  
 x Coordinates: 0.420  
 y Coordinates: 0.420  
 Luminosity (%): 100.00  
 Dominant (nm): 530  
 Complementary (nm): 430  
 Excitation Parity: 0.351



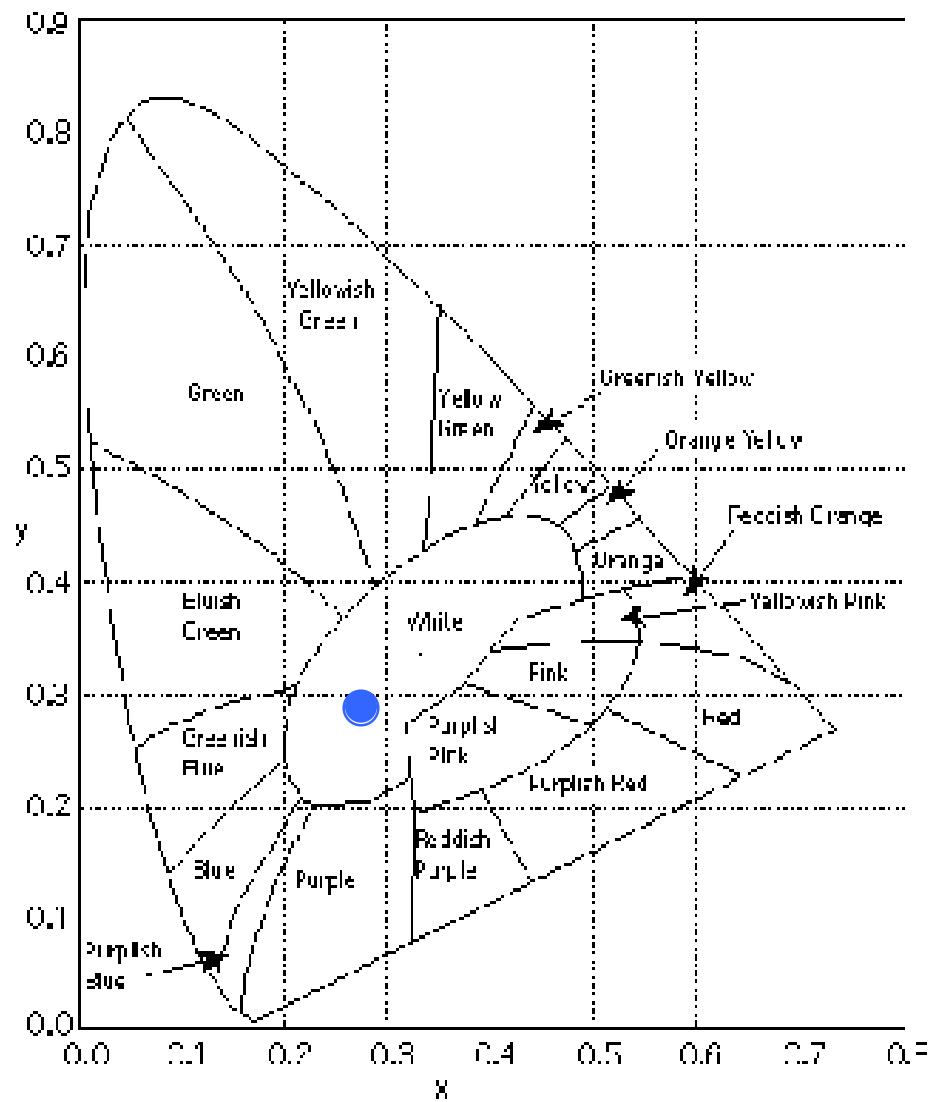


Color Standard: 1931 CIE  
 Field of View: 2°  
 Polarization: Average  
 Reference White: CIE-C  
 Illuminant: 6000KBE  
 Incident angle (deg): 0.0°

Trans:  
 x Coordinate: 0.322  
 y Coordinate: 0.322  
 Luminosity (%): 100.00  
 Dominant (nm): 572  
 Complementary (nm): 472  
 Excitation Parity: 0.07%







Color Standard: 1931 CIE  
 Field of View: 2°  
 Polarization: Average  
 Reference White: CIE-C  
 Illuminant: 10000K65  
 Incident angle (deg): 0.00

Trans  
 x Coordinate: 0.281  
 y Coordinate: 0.298  
 Luminosity (L): 100.00  
 Dominant (nm): 478  
 Complementary (nm): 578  
 Excitation Purity: 0.139



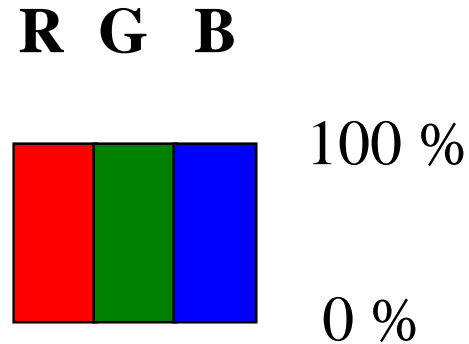
# Some Other Applications of Additive Color Mixing

- Color of sun/sky
  - Look at Light Matters poster
- TV/Computer monitors
  - Look at Light Matters poster
  - Look at CRT monitor



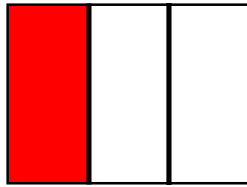
# Group Assessment - try this

- How are the following colors produced on a color monitor:
  - Red
  - Yellow
  - White
  - Light red
  - Dark red
- Use R G B bar charts

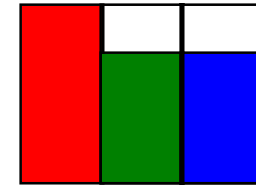


# Bar charts for additive color mixing - light

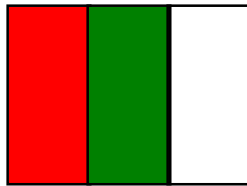
Red



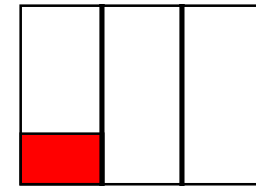
Light Red



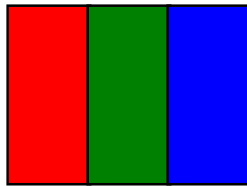
Yellow



Dark Red

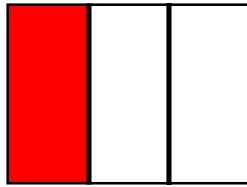


White

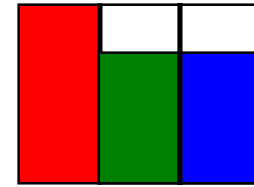


If you start with white light (daylight), how do you generate these colors?

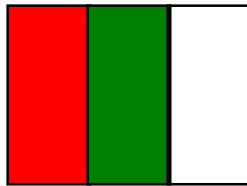
Red



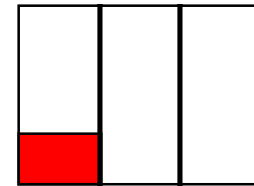
Light Red



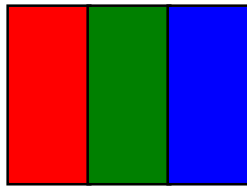
Yellow



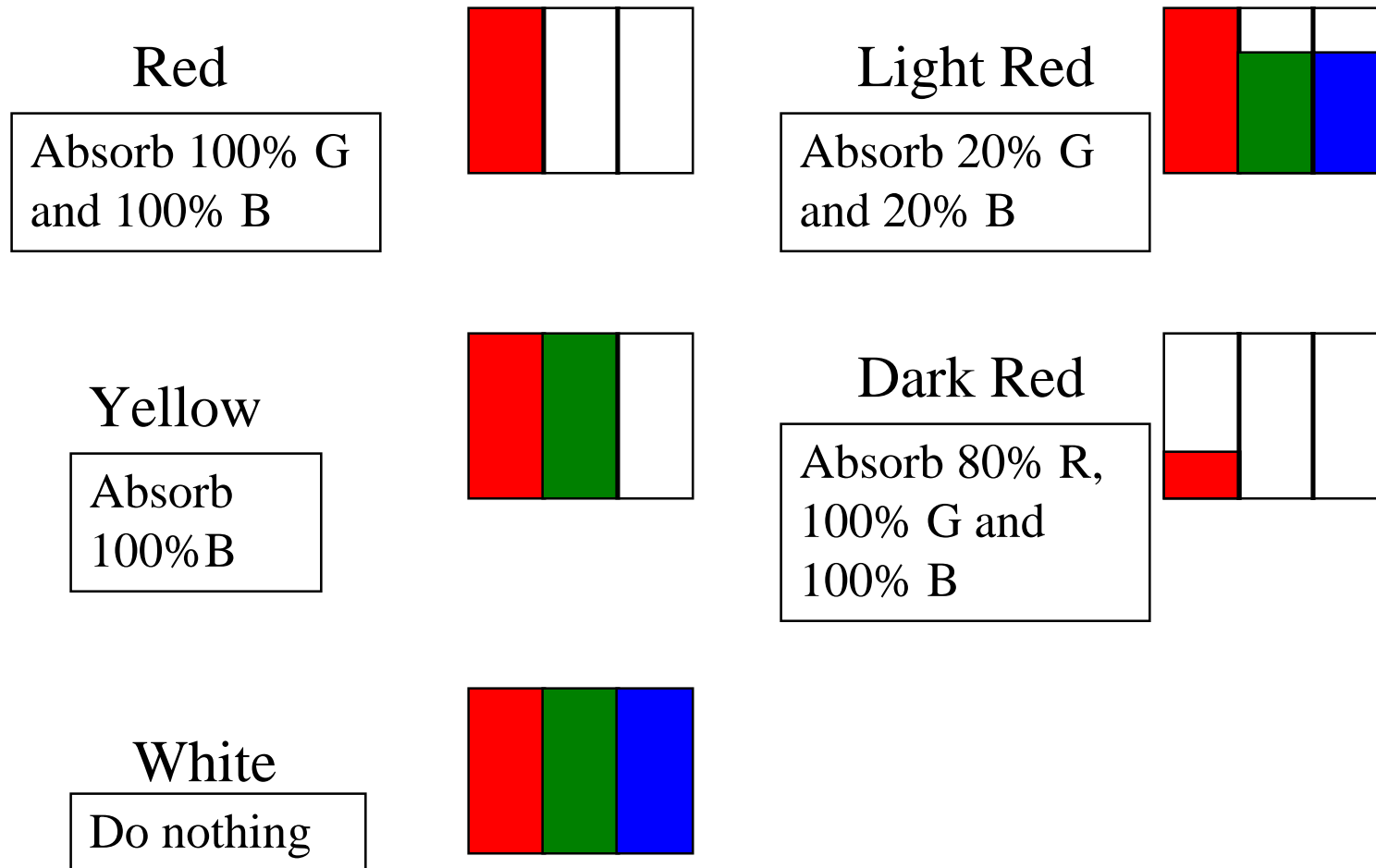
Dark Red



White



If you start with white light (daylight), how do you generate these colors?



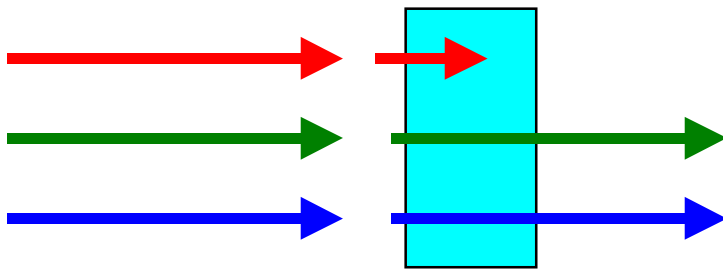
To generate colors, starting with white light

- Printers, painters need to generate colors starting with white light -room light, day light
- You need a red light absorber, a green light absorber, and a blue light absorber, at percentages ranging from 0 to 100%
- What color will these light absorbers appear in white light?



To generate colors, starting with white light

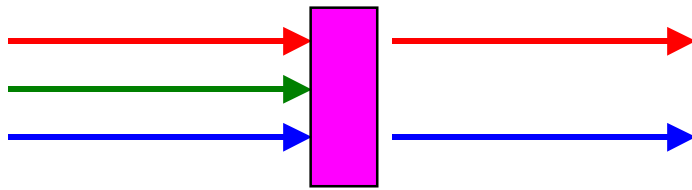
- A red light absorber absorbs red light, so it appears cyan in white light:  $W-R=G+B$
- Note that it would appear green in green light or yellow light and blue in blue light or magenta light. So the only true statement we can make about it is that it is a red light absorber - we cannot truly describe it by its apparent color.



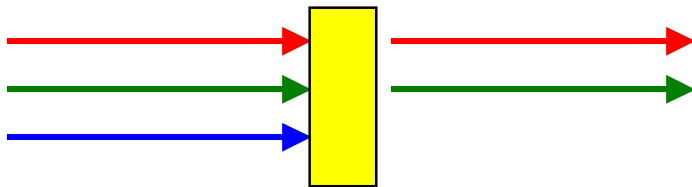


## To generate colors, starting with white light

- A green light absorber absorbs green light, so it appears magenta in white light ( $W-G=R+B$ )



- A blue light absorber absorbs blue light, so it appears yellow in white light ( $W-B=R+G$ )



## What colors should printers use to generate a wide range of colors?

- We want to be able to generate 0-100% of combinations of red, green and blue light
- Need:
  - Red absorber – cyan ink
  - Green absorber – magenta ink
  - Blue absorber – yellow ink
- Need to be able to print inks at coverages ranging from 0-100%



How could printers generate R, G, B  
using C, M, Y inks?

- Use films to verify your predictions.



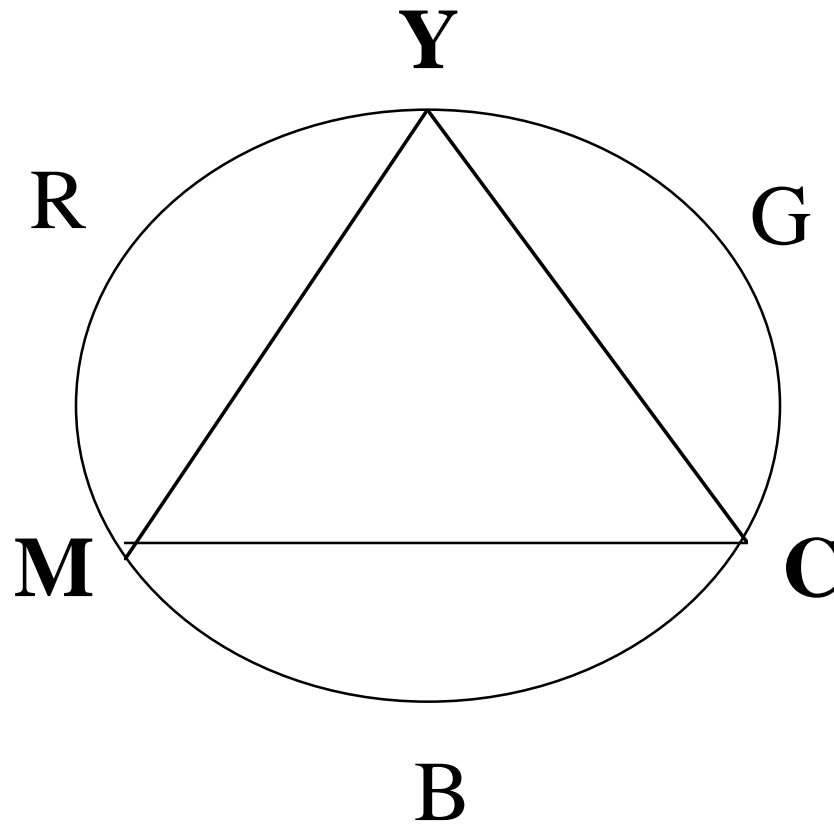
# Generate RGB light using CMY inks in white light

- Overlap M and Y transparencies on W paper
  - Red (M film absorbs G light, Y film absorbs B light)
- Overlap Y and C transparencies on W paper
  - Green (Y film absorbs B light, C film absorbs R light)
- Overlap C and M transparencies on W paper
  - Blue (C film absorbs R light, M film absorbs G light)



# Color Wheel Model for Subtractive Colors (Pigments)

*Color wheel for light and pigments is the same!*



# Complementary Colors of Pigment

- Overlapping complementary colors of pigment produce black
- Use color math to show this:
  - R, C pigments:  $W-R-G-B = K$
  - G,M pigments:  $W-G-R-B = K$
  - B,Y pigments:  $W-B-R-G = K$
- Complementary colors lie on opposite sides of the color wheel
- Demonstration using complementary color films, 2 color wheels
- Demonstration using interference filters



# How could printers generate 0-100% R, G, B using C, M, Y inks?

- Dilute each ink for each colored area
- Have extremely dilute inks and use multiple passes to achieve desired color
- Print very small areas with different area coverage so that your eye blends the areas with ink and the areas without the ink



# Use of Gradient Strips

- How are colors besides CMYRGBK produced?
- Experiment with CMYK strips
- Try to match a color on your magazine page.
- What are the color coordinates of the color – ie the CMYK percentages?
- Then compare how the gradient strip produced the color to how the color was actually produced – observe using your hand-held microscope.





# Group assessment - try this.

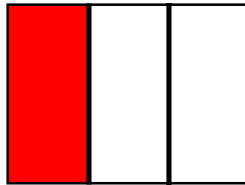
- How are the following colors produced using a color printer:
  - Red
  - Yellow
  - White
  - Light red
  - Dark red



If you start with white light (daylight), how do you generate these colors?

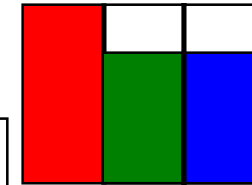
Red

Absorb 100% G  
(M film) and 100%  
B (Y film)



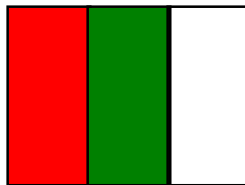
Light Red

Absorb 20% G  
(20% M film)  
and 20% B  
(20% Y film)



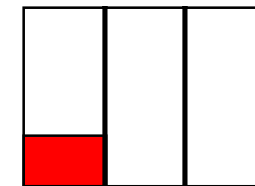
Yellow

Absorb 100%B  
(Y film)



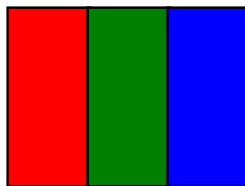
Dark Red

Absorb 80% R  
(80% C film),  
100% G (M film)  
and 100% B (Y  
film)



White

Do nothing



# Applications of Subtractive Color Mixing

- Color Printing
  - Use hand-held microscope
  - Find examples of CMY strips on cereal boxes, magazines, ...
- Color of water (see Light Matters poster)
  - Glass of water
  - Pool or ocean
- Color of grass (see Light Matters poster)
- Energy conservation – color of clothes





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4-17-01



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# Ways to Explore Subtractive Color Mixing (Pigments: Ink or Paint)

- **Colored (absorbing) transparencies**
- Interference filters
- Paint
- Colored water
- Shine laser light through films
  - Bonus: Diffraction pattern due to dot printing pattern
- RGB LED light mixer
- Simulation using CMY model in Word
- Simulation using CMY model- web applet
- Zip lock bags



# Recent example of change from subtractive to additive color

- Traffic lights
  - Old style: white light source, green cover
  - New style: green light emitting diodes
- Why the change?
  - Light emitting diodes are more efficient
    - Much energy lost to green cover (R, B absorbed)
  - Multiple light sources - 100 LEDs
    - If one burns out, the signal still operates
  - LEDs have longer lifetime - lower maintenance costs
- White LEDs for lighting is focus of much R+D



# What about the artist's primary colors? Red, Yellow, Blue

- Overlap R and Y transparencies on W paper
  - Resultant color?
- Overlap R and B transparencies on W paper
  - Resultant color?
- Overlap Y and B transparencies on W paper
  - Resultant color?





# R, Y, B Primaries

- Overlap R and Y transparencies on W paper
  - Red
- Overlap R and B transparencies on W paper
  - Black
- Overlap Y and B transparencies on W paper
  - Black

*R, Y, B are not appropriate primaries*

*Traditional artist's color wheel is incorrect*

Exercise for the interested teacher: Use bar graph model to theoretically demonstrate why RYB fail as primaries.



# Other Simple Color Models

- Color cube
  - Sold as a model for C, M, Y – subtractive color mixing
  - Also a model for R, G, B – additive color mixing
  - Note that color cube is a more complete model than the color wheel
  - Distance between color coordinates quantifies color differences



# Theory of Color Vision and Implications

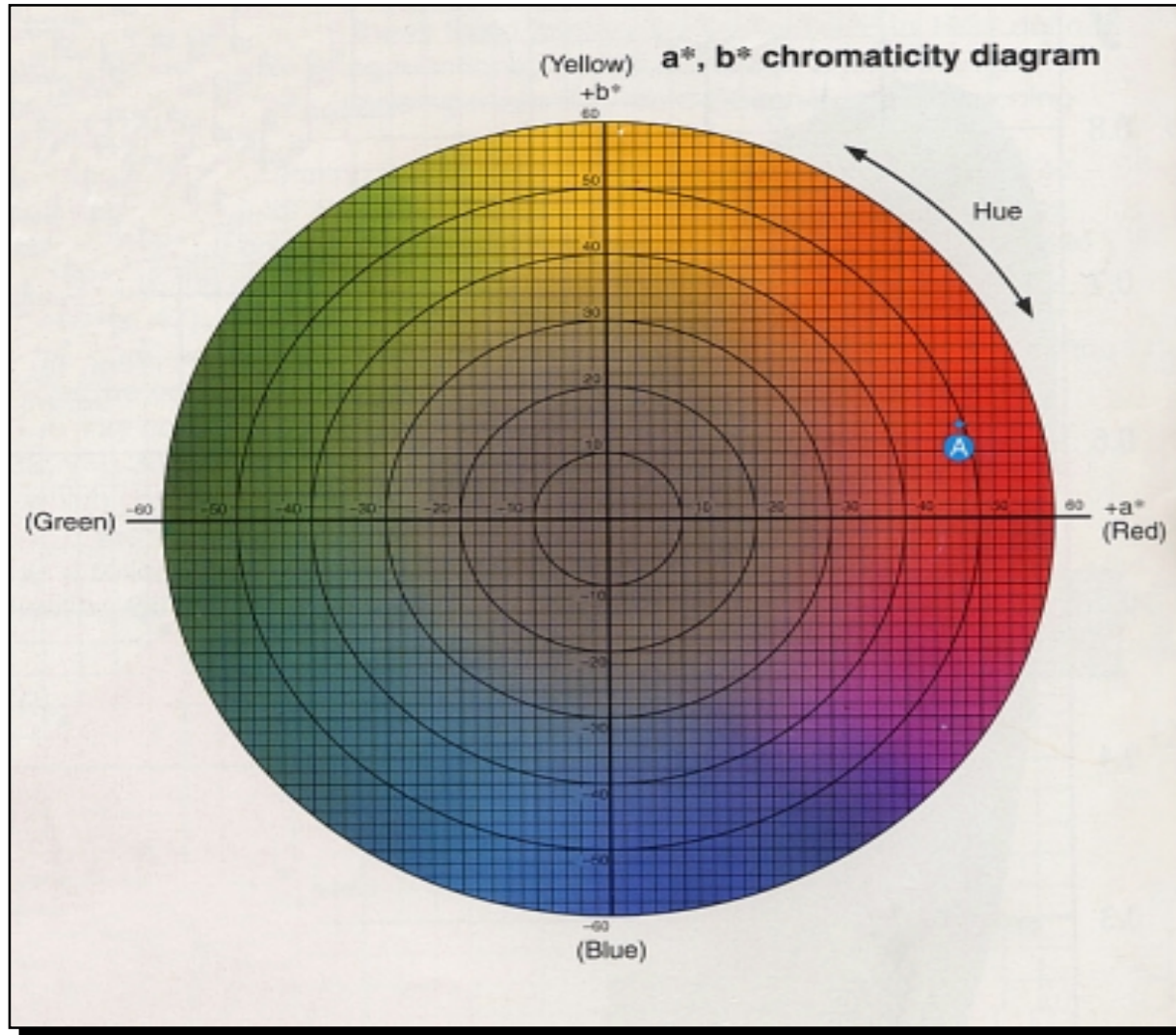
- Red (R), Green (G), and Blue (B) cones
  - R(L-long wavelength), G(M-mid wavelength), B(S-short wavelength)
- 3 cone responses are processed to become 3 color receptive responses
  - R+G yields brightness and perception of yellow
  - R-G yields red or green response
  - (R+G)-B = Y-B yields yellow or blue response



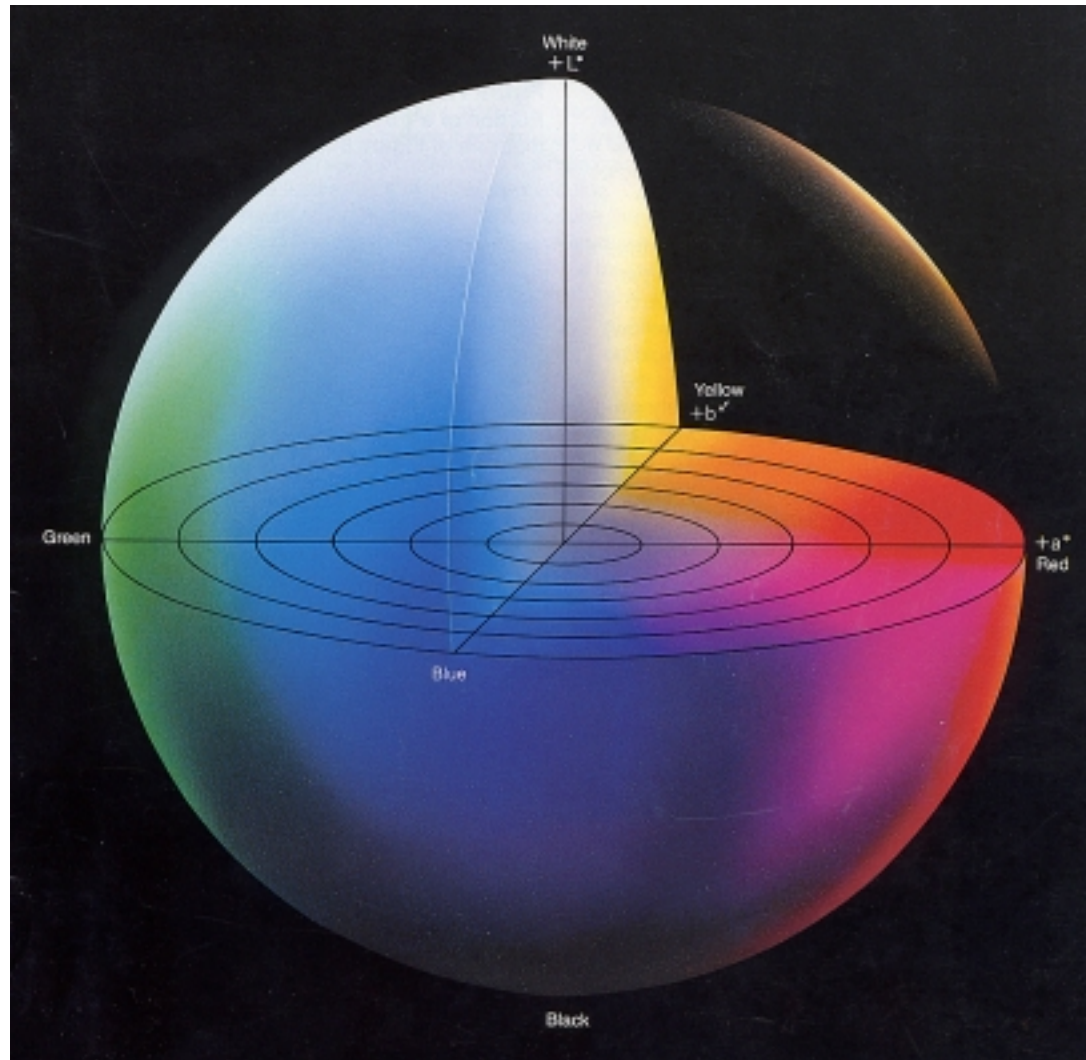
# Theory of Color Vision and Implications

- Implications:
  - We see 4 distinct colors: R, G, Y, B - basis for L\*a\*b\* color space
  - We do not see reddish greens or yellowish blues
  - The blue cone does not contribute to brightness so images that only differ in brightness of blue are difficult to see. This is why blue is hard to see at night and why blue on black is a terrible choice for web pages. See example of colors printed at different lightnesses.





# L\*a\*b\* COLOR SPACE



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# Conclusion-Color Clarification

- Combinations of R, G, and B light produce largest variation of colored light compared to any other 3 colors of light
- Primary colors of pigment are C, M, Y
- Need to always specify if we mean
  - color of light
  - color of an object as seen in white light (absorbs colors of light)
- Colors in nature can be understood using rules of color mixing

