### Physics in Entertainment and the Arts

#### Chapter XVI

### The Algebra of Color

**Back to Superposition**
- When we talked about wave interference, we concentrated on sound.
- However, all types of waves undergo interference effects.

Here we see water waves undergoing interference.

**Back to Superposition**
- Light waves (electromagnetic waves) also display interference effects.
- At any point in space, the light seen is just the sum total of all the photons present.

**Back to Superposition**
- Just as for sound...
  - the ear was where the important effects took place
  - sum & difference tones
  - the most important effects for light take place in our eyes.

**Back to Superposition**
- Our eyes, working with our brains, add light waves in various ways.
- We see these additions as colors.
- And most times the colors we see aren’t really there!
  - Remember the difference tones...

### Combining Colors

**Combining Colors**
- Superposition implies an adding of waves.
- But, in fact, for color there are two ways to combine waves:
  - An additive process
  - A subtractive process.

**Combining Colors**
- An additive process is combining colors by adding one color to another.

**Combining Colors**
- A subtractive process is combining colors by subtracting certain colors from a wide range of starting colors (white light).

Blue filter
Green filter
Additive Color
• The spectrum of white light was discovered by Isaac Newton in 1666 AD

Additive Color
• Plotting this spectrum on a color purity diagram yields:

Additive Color
• Human experiments show that this entire spectrum can be very well represented – by an appropriate mixture of only three additive primary colors

Additive Color
• Note that these 3 colors are not saturated colors, they consist of many different wavelengths!
• For example, the light represented below would be typically seen as “green”

Additive Color: Red + Green
• If we add the red spectrum (R) with the green spectrum (G), we find that the resulting color is yellow (Y) to our eyes
• “Algebraically”, \( R + G = Y \)

Additive Color: Green + Blue
• If we add the green spectrum with the blue spectrum (B), we find that the resulting color is cyan (C)
• cyan is a light bluish-green color
• Or, \( G + B = C \)

Additive Color: Blue + Red
• If we add the blue spectrum with the red spectrum, we find that the resulting color is magenta (M)
• magenta is a purplish color
• Or, \( R + B = M \)

Additive Color: R + G + B
• Lastly, adding all 3 additive primary colors yields white light (W)
• \( R + G + B = W \)
• What this all means is that we can make any color in the white light spectrum – by mixing only 3 colors in various proportions!
Additive Color: \( R + G + B \)

- This is how a television screen can form thousands of shades of color using only 3 electron beams

- The electron beam (not really colored) hits the appropriate phosphor pixel to create one additive primary color
- By varying the intensity of each beam, any color can be created!
- By sweeping the beams across the shadow mask, the beams only hit their intended pixels

Eyes versus Ears

- When presented with two notes which produce an audible beat frequency…
  - Called a difference tone
- …the ear hears all three tones
  - including the one that isn’t really there!

- However, when presented with two colors which produce a third color…
  - …the eye does not see all three colors it only sees the one that isn’t really there!
- However, this disadvantage is offset by the much better spatial resolution of the eye

Additive Color: \( R + G + B \)

- Since our eyes cannot distinguish the individual pixels from a distance…
- …our eyes blend the three colors into one “average” color

Subtractive Color

- While the additive primaries correspond to the presence of 2/3 of the white light spectrum…
- …the subtractive primaries correspond to the absence of 1/3 of the white light spectrum

- Since inkjet printers usually print on white paper, they use the subtractive color process
- Most inkjet printers need 4 color cartridges – black, yellow, magenta, and cyan
- Using these colors in various combinations, the printer can produce thousands of different shades of colors!
Subtractive Color
• The subtractive color process (using color filters) can also produce the additive primary colors
  \[ W - Y - C = G \]
  \[ W - C - M = B \]
  \[ W - M - Y = R \]

Subtractive Color
• Thus subtractive pairing of the subtractive primaries yields the additive primaries
  • A photographer only needs three subtractive primary filters…
    – yellow, cyan, and magenta
  • …to create the three additive primary filters!
    – red, green, and blue

Subtractive Color
• Since
  \[ R + G + B = \text{White} \]
  Then
  \[ Y + C + M = \text{Black} \]
• By symmetry…

Subtractive Color
• Adding all three additive primaries
  – yields all colors (white light)
• Subtracting all three subtractive primaries from white light
  – yields no colors (black light)

Complementary Colors
• Since \( W = R + G + B \), and since \( G + B = C \)
  • Then \( W = R + C \)
  • Any two colors which, when added, yield white light
    – are called additive complementary colors

Complementary Colors
• Other additive complementary colors are
  \[ W = B + Y \]
  \[ W = G + M \]

Complementary Colors
• Colors opposite each other are complementary: