# Light and Color

# Light

Light is *electromagnetic radiation* in the *visible spectrum*.

- The range of wavelength of visible light is from <u>400nm to 700nm</u> (1 nm (nanometer) $= 10^{-9}$ meters).
- Color is determined by the dominant wavelength.
- The brightness is determined by the intensity of the radiation.

Note: *Intensity* describes the physical amount of energy. *Brightness* describes our perception of this energy.

Light and color are complicated, because

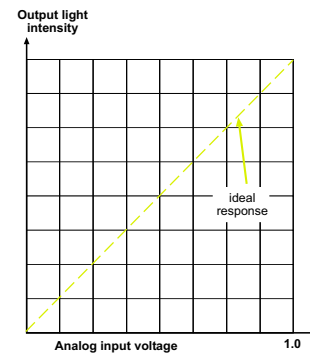- the *physics* of light is very complex.

- our *perception* of light is a function of our eyes, which perform numerous unconscious corrections and modifications. For example, the equal intensity of colored light are perceived as being of different brightnesses depending on the color.

- *hardware devices* can only approximate colors to a limited precision.
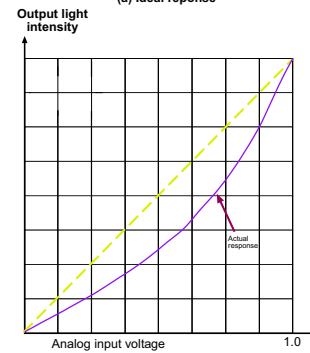
# Gamma Correction

*Achromatic light* is only characterized by *intensity*. We assume that intensity values are specified as a number from 0 to 1.

*Problem:* Human perception system for light and color is nonlinear. Our eye cannot perceive the linear variation of brightness for linear variation of the intensities. The reason is that the eye is sensitive to the ratios of intensities, rather than absolute differences. Therefore, to achieve *perceptual* uniformity, intensities should be shoosen on a *logarithmic*, rather than a linear scale.
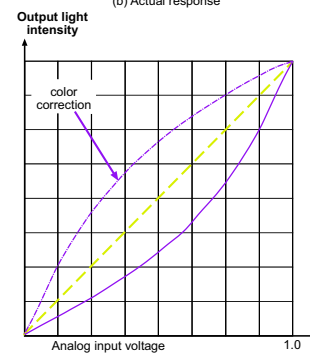
*Gamma correction:* Most graphics monitors provide a form of automatic correction so that a linear variation in the supplied intensity values (e.g. RGB) generates a perceived linear variation in brightness.

**Output light intensity**

ideal
response

**Analog input voltage**　　1.0

(a) Ideal reponse

**Output light intensity**

Actual
response

Analog input voltage　　1.0

(b) Actual response

**Output light intensity**

color
correction

Analog input voltage　　1.0

(c) Color correction
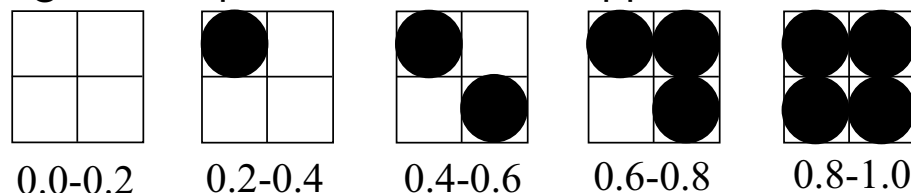
# Halftone Approximation

*Problem:* Graphics devices only provide a discrete set of choices, not a continuous range of intensities.

Extreme case: monochrome display: only 2 colors: white and black

How to use a small number of colors or shades to produce the perception of many colors or shades? **halftone approximation**

*Dithering*

Grouping pixels into groups, e.g. $2 \times 2$, or $3 \times 3$, and assigning the pixels of the group to various intensities. Using $n \times n$ pixels allows us to approximate $n^2 + 1$ intensity levels.

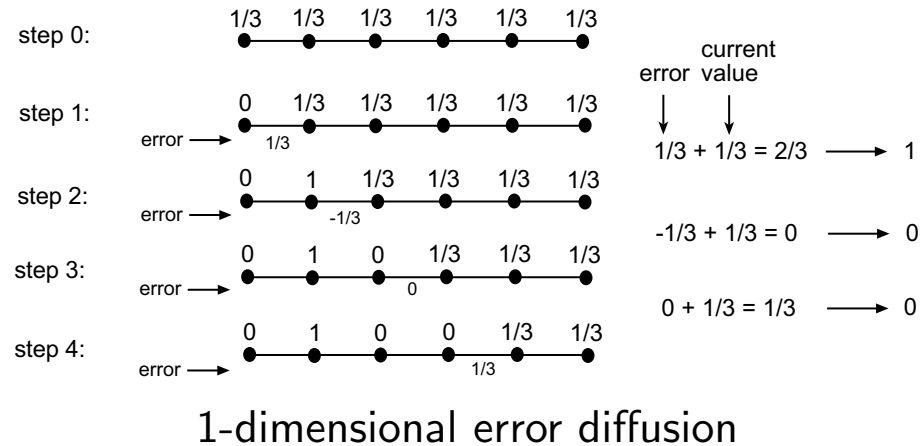| 0.0-0.2 | 0.2-0.4 | 0.4-0.6 | 0.6-0.8 | 0.8-1.0 |
|---------|---------|---------|---------|---------|

Halftone approximation with dither patterns

## *Error Diffusion*

When we approximate the intensity of a pixel, we generate some approximation error. If we create the same error at every pixel then the overall image will suffer. Keep track of these errors, and use later pixels to correct for them.

**One dimension:**



1-dimensional error diffusion

## Two dimension: Floyd-Steinberg method
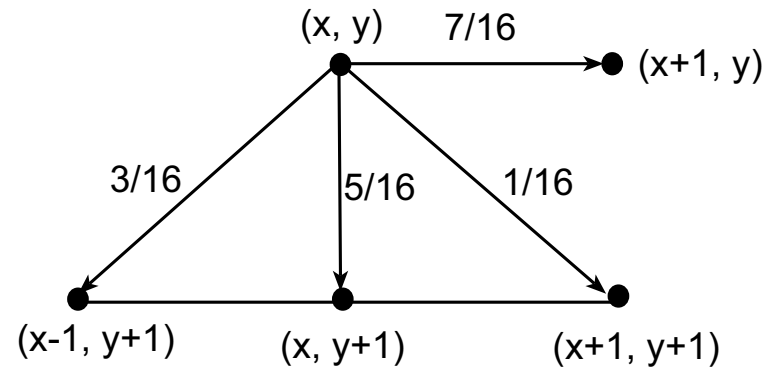


Floyd-Steinberg's Error distribution (2-dimension)

Let $S[x][y]$ denote the shade of pixel $(x, y)$. To draw $S[x][y]$ we round it to the nearest available shade $K$ and set $err = S[x][y] - K$. Then we compensate by adjusting the surrounding shades. e.g. $S[x+1][y]+ = 7/16err$.

Rather than thinking of shades as simple scalar values, let's think of them as vectors in a 3-dimensional RGB space. We can generalize Floyd-Steinberg method to colored images.

## Color and Color Model

# What is Light and Color?

Light and color are perceived and reproduced depending on a complex interplay between:

- the physics of light
- the biology of the human perception system
- the nature of the hardware device (CRT monitors, photographic and video cameras, offset printers, etc).

*Spectral Power Distribution* (SPD): Describes the amount of power of each wavelength of light in the visible spectrum.

Our visual system takes the combination of 3 types of cones and what we perceive is called *color*.

Because our perception of color is dependent on a combination of 3 values, most color systems describe color as a point in a 3-dimensional space.

*Lightness* (or *brightness*) are not physical quantities, but perceptual quantities. It is a complex function of linear light, but there are two components.

- We are more sensitive to light in some spectral ranges than others. For example, given equal amounts of red, green and blue light, we will perceive the green as being the brightest, red second, and blue a distant third.

- Our perception system is *nonlinear*. It responds logarithmically to increases in intensity. That is, we perceive differences in terms of *ratios* of intensities rather than absolute differences.

# Luminance

- *Luminance* accounts for the sensitivity of our eye to different spectral ranges. For equal intensities of blue and green light, the blue light will have much lower luminance than the green light.

- Luminance is just intensity multiplied by a *luminance-efficiency function* for the human eye. This function is 0 outside the visible spectrum (400 to 700 nm) and peaks near green at around 555 nm.

- The luminance (linear brightness) of an SPD is a scalar quantity. To compute this you integrate the SPD using the luminous-efficiency function as a weighting function. This quantity is denoted by $Y$, by the CIE (Commission Internationale de l'Éclairage).

- Note that luminance is still a linear quantity. It does not take into account the logarithmic nature of perception. Thus, gamma correction would have to be applied to scale the light to a perceptually smooth range of values.

# CIE Chromaticity Diagram

*Problem:* How to describe a color mathematically?

*Answer:* Define 3 *primary colors*, from which all other colors can be produced by taking appropriate additive combinations.

What should these primaries be? It is not generally possible to completely span the color space using additive combinations of three standard colors (such as red, green, and blue). In particular, no matter which colors you use, some subtraction is needed.

The CIE defines three standard primaries named $X$, $Y$ and $Z$, so that colors can be made through a strictly additive process. The value $Y$ is just the luminance. Think of these functions as weighting functions which can be applied to an SPD for each wavelength $\lambda$, denoted $\bar{x}(\lambda)$, $\bar{y}(\lambda)$ and $\bar{z}(\lambda)$.

To map an SPD, given by $P(\lambda)$ into a 3-element vector, we integrate using these weighting

functions:

$$X = k \int P(\lambda)\bar{x}(\lambda)d\lambda$$

$$Y = k \int P(\lambda)\bar{y}(\lambda)d\lambda$$

$$Z = k \int P(\lambda)\bar{z}(\lambda)d\lambda.$$

where $k$ is a scaling factor. Thus, any color can be described as a 3-element vector in $(X, Y, Z)$ space by adding these primaries.

This is a 3-dimensional space, and hence is hard to visualize. A common way of drawing the diagram is to consider a single 2-dimensional slice, by normalize by cutting with the plane $X + Y + Z = 1$. We can then project away the $Z$ component, yielding the *chromaticity coordinates:*

$$x = \frac{X}{X + Y + Z} \qquad y = \frac{Y}{X + Y + Z}$$

(and $z$ can be defined similarly). These components describe just the color of a point. Its brightness is a function of the $Y$ component.

Different groups define colors slightly differently, but the CIE coordinate space is widely regarded as an international standard. A nice feature of the $XYZ$-space is that we can predict the effect of additively combining various colors.

One shortcoming of CIE is that equal distances between colors do not produce perceptually equal changes. An alternative system called CIE LUV attempts to correct this.

# Raster Graphics Color Models

The CIE model is useful for providing formal specifications of any color as a 3-element vector, however it is not the easiest way to produce color in hardware. Typical hardware devices like CRT's, televisions, and printers use other standards that are more convenient for generation purposes. Unfortunately, neither CIE nor these models is particularly intuitive from a user's perspective.

# RGB Color Model

The RGB model uses the additive primaries red, green, and blue. So (assuming our normalization from 0 to 1), red is $(1, 0, 0)$, green is $(0, 1, 0)$, and blue is $(0, 0, 1)$. These colors can be added to make other colors, black is $(0, 0, 0)$, white is $(1, 1, 1)$.
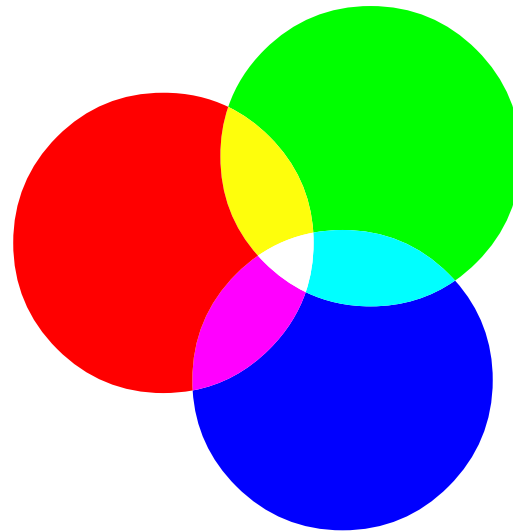
Three primaries: red, green, and blue

# CMY Color Model

RGB is an additive color system. However, most printing devices use a subtractive system. This means that the ink absorbs a particular color, and hence what you see is what is reflected (not absorbed). When inks are combined, they absorb a combination of colors, and hence the reflected colors are reduced, or subtracted.

*Subtractive primaries* are cyan, magenta, and yellow. It is very easy to convert from RGB to CMY (and vice versa), by simply subtracting each component from 1

$$(C, M, Y) = (1 - R, 1 - G, 1 - B).$$

Thus in the CMY model, black is $(1, 1, 1)$ and white is $(0, 0, 0)$.

A variation of CMY is CMYK, where an extra redundant component K has been added to represent black.

# YIQ Color Model

The YIQ model is used in the US for color television broadcasting. It is a recording of RGB with some tricks for broadcasting efficiency and compatibility with black-and-white. The Y component is equal to the Y component of the CIE standard. This is basically a measure of luminance, so black-and-white sets simply display this one component. The I and Q components encode hue and saturation. Since our visual system is more sensitive to variations in luminance, the I and Q components can be transmitted with lower bandwidth that what is used for Y.

# User oriented systems

The models RGB, CMY, and YIQ are tailored for particular devices (CRT's, printers, and video). User's find these systems difficult to work with. For this reason there are systems that describe colors in terms that are more natural. For example, the HSV system defines color in terms of hue (color), saturation (purity), and value (lightness).

# Reading Assignment and News

Chapter 2 pages 57 - 64, of Recommended Text.

Chapter 6 pages 267 - 274, of Recommended Text.

Please also track the News section of the Course Web Pages for the most recent Announcements related to this course.

(http://www.cs.utexas.edu/users/bajaj/graphics23/cs354/)