Light and Color

CSC 292:
Computer Graphics

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Color Perception and Representation

- Complex subject.
- Involves Physics, Psychophysics, Physiology, Psychology, Art, etc.
- Color Perception depends on properties of object, light, surroundings, and human visual system.
- Hard to predict what color a person will "see"

Achromatic Light

- Black and white TV.
- Only concerned with *quantity* of light.
- Terms *intensity* and *luminance* - Physically defined.
- Term *brightness* - perceived intensity, subjectively defined.
- Deal with intensities on a 0-1 scale.

Selecting Intensities

- If we have (say) 256 intensities for a CRT, what should they be?
- Not 128 from 0 to 0.1, and 128 from .9 to 1.0...
- Linear might seem a good idea but...
- Perceptual brightness is much closer to a logarithmic process (step from .10 to .11 seems the same as step from .50 to .55.
- Steps should be placed logarithmically in interval from lowest attainable intensity I_0, to 1.0.

- For example, 4 steps between $1/8$ and 1 would be $1/8$, $1/4$, $1/2$, and 1.
- In general $I_0 = I_0, I_1 = rI_0, i_2 = r^2 I_0 ...,$ where $r = (1/I_0)^{1/n}$.
- Note critical dependence on I_0. Lowest intensity is never zero. Typical values for CRTs are $1/200$ up to $1/40$.
- Ratio between highest and lowest intensities for a device is known as the *dynamic range*.

Gamma Correction

- Once we know the desired intensities, displaying them is a bit tricky, and recording them on film even trickier.
- This is because CRT intensity is related to beam current N by a relationship of the form $I = kN^\gamma$ for constants k and γ.
- Values sent to the CRT must thus be *gamma corrected*, unless the display has gamma correction hardware.
- If logarithmic and gamma correction are not done, then steps at the darker end of the range are much more noticeable than steps at the bright end.

Number of Steps

- Total dynamic range of the eye is on the order of 10^7 (!) with a number of adaptive mechanisms included (e.g. pupil dilation, slow dark adaptation etc.)
- The human eye cannot distinguish values that differ by less than about 1%.
- We can use this to determine the number of intensities needed to cover a given dynamic range.

- The formula is:

$$r = 1.01 = (1/I_0)^{1/n} \Rightarrow n = \log_{1.01}(1/I_0)$$

Medium	Dynamic Range	n
CRT	50 - 200	400-530
prints	100	465
slides	1000	700
newsprint	10	234

- Blurring reduces n for print media. 64 can be taken as a minimum for good results.

Halftone Approximation

- Many devices print only in black and white.
- Effect of gray can be obtained by using *spatial integration* properties of the eye.
- In print media, an array of variable sized dots is used. This is called *halftoning*.
- Spacing varies from 60 - 200 dots per inch.
- In array output devices, gray tones are produced by *dithering*.

- One way is to use $n \times n$ subpatterns to provide $n^2 + 1$ intensity levels.
- Tradeoff between spatial resolution and intensity resolution.
- Patterns can be specified by a *dither matrix*, e.g.

$$\begin{bmatrix} 6 & 8 & 4 \\ 1 & 0 & 3 \\ 5 & 2 & 7 \end{bmatrix}$$

- To display intensity I we turn on all pixels less than I.

Clustered Dithers

- If output device is poor at isolated pixels (e.g. laser printers) it may be necessary to cluster dots. Known as a *clustered dot ordered dither*.
- Patterns must be carefully designed not to introduce artifacts
  - Avoid linear patterns.
  - Grow from center.
  - Produce a growth sequence (automatically done with matrix representation).
- To produce equivalent of 150 dpi printed half-toning thus requires 8×8 or 10×10 masks, and a pixel resolution of 1200 to 1500 dpi.
- We can dither with more than 2 gray levels as well (e.g. 4).

Dispersed Dithers

- On CRTs and some other devices, single pixels work perfectly well.
- On these we can use *dispersed dot ordered dither*.
- Many possible patterns. Try to design to reduce texture artifacts.
- Quite a difficult problem.
- Random is very bad (hence order).
- Perfect order produces obvious patterns at some gray levels.

Other Issues

- If we do not have extra pixels available, we can still use these techniques, essentially by tiling image with dither matrix and applying comparison rule at each pixel.
- This allows the use of large, carefully designed dither matrices (e.g. *blue-noise* techniques).
- Another technique is known as *error diffusion*.
- Difference between displayed value and desired value is passed to neighboring pixels (e.g. 7/16 E, 3/16 SW, 5/16 S, and 1/16 SE).
- Small images displayed on large windows may be interpolated to avoid blocky appearance.

COLOR

- Discussions of color *perception* Usually use the terms hue, saturation, and lightness.
- Subjective terms, not originally defined technically.
  - *Hue* distinguishes shades such as red, green, blue, etc.
  - *Saturation* refers to distance from gray of equal intensity (red is saturated, pink is unsaturated).
  - *Lightness* refers to total amount of light or brightness.

- Need a way of specifying and measuring colors.
- For reflected light, we can compare against a set of “standard” color chips, organized by hue, saturation and value (lightness), in standard lighting.
- The Munsell system is one such standard set.

Psychophysics

- Chip-matching is somewhat subjective - depends on lighting, surrounds, etc.
- More quantitative approaches are obtained in a branch of psychophysics known as *colorimetry*.
- Any light signal can be described by a curve, the *spectral distribution*, graphing the amount of energy present at each wavelength in the visible spectrum (approximately 400 - 700 nm).
- Describing such a curve requires many (infinitely many) numbers.

- It turns out that the visual impression produced by any spectral distribution can be described by just three numbers.
- This is due to the fact that color perception arises from the differential responses of three types of *cone cells* in the retina, each with a different spectral response curve.
- Peaks: "blue" at 440 nm, "green" at 545 nm and "red" at 580 nm.
- Many different spectral distributions must thus map to identical perceptual colors.
- Distributions that map to the same perception, as determined by color matching experiments, are called *metamers*

Color Matching

- Basic experimental protocol is side-by-side *color matching experiments*: Subject is shown two distributions, and asked whether they appear to be the same color.
- Results are consistent within individuals: If two distributions look the same now, they look the same in later experiments.
- Results are largely consistent between individuals: Distributions that look the same to one person, look the same to others (with the exception of rare people with anomalous color perception).
- Results are not consistent between people and other animals: Certain spectra that are distinguishable by humans are not distinguishable by some animals, and vice versa.

Color Specification Systems

- There are several methods of assigning three numbers to specify colors.
- The first attempts to formalize the old artists' hue, saturation, and lightness scheme.
- Based on the observation that any spectral distribution can be matched by a combination of white light and a spike of a single wavelength. (Except purples, which need a red spike and a blue spike.)

- The three terms are:
  - *Dominant wavelength*, corresponding to notion of hue. Equal to the wavelength of the added spike.
  - *Excitation purity*, corresponding to the notion of saturation. Equal to the ratio of the energy in the spike to the total energy.
  - *Luminance* corresponding to the notion of brightness. Equal to the total energy in the sample, sometimes normalized by the energy of a bright white standard.

Tristimulus Theory

- The second method is known as the *tristimulus theory*, and is based on the observation that many colors can be exactly matched by a mixture of three monochromatic primaries.
- Primaries are defined as the blue, green, and red lines at 438.1 nm, 546.1 nm, and 700 nm respectively.
- By performing a series of color matching experiments on monochromatic colors, three curves called *color matching functions* is obtained showing the proportions of each primary required to match the monochromatic line.

- The proportions required for mixed spectra can then be obtained by integrating the product of the spectral curve with the corresponding color matching function.
- Only drawback is that while most colors are matchable, some of the monochromatic colors in the blue-green part of the spectrum require *negative* amounts of the red primary. (Measured by adding red to the sample side in the matching experiment).

The CIE System

- A third method, the *CIE Chromaticity system* defined three primaries X, Y, and Z to replace the red, green and blue primaries.
- All monochromatic colors, and hence all perceptible colors, could be produced with positive combinations of these three primaries.
- Spectra of the primaries themselves contain negative amounts of some wavelengths, and thus these primaries are "imaginary" in some sense.
- A useful standard, nevertheless, since the perceptual representation for any spectral distribution can be found by integrating the product of the spectrum and the color matching functions, just as before.

- Normalizing by dividing X, Y, and Z by (X + Y + Z) to obtain x, y, and z gives a representation that depends only on hue and saturation, and can be given by providing only two of the coordinates (e.g. x and y).
- Plotting the monochromatic curve in x and y gives a *chromaticity diagram* that is useful for illustrating color mixing properties.
- All perceptual colors lie within the curve
- Any hue that can be obtained by mixing two colors lies on the line between them.
- Any hue that can be obtained by mixing three colors lies inside the triangle defined by them (and more generally in the convex hull).
- Useful for determining how much of the perceptual range can be covered by certain sets of primaries.