Color and Perception

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A SLIGHT DETOUR

• We’ve spent the whole class talking about how to put images on the screen

• What happens when we look at those images?

• Are there any properties of human perception that we can take advantage of?

• OF COURSE!
Understanding vision

• Humans are quirky in what they can and can’t see
• We’re very tolerant of certain types of errors...
• ... and others jump right out at you
• Learning about how vision works can give us a serious leg up
• Spend more time rendering the things we notice, and less time rendering the things we don’t
• Light is just streams of photons
• Photons exhibit wave/particle duality
• Massless, but carry energy proportional to their frequency \((c / \lambda)\)
When photons in certain frequency ranges are received in our eye, we perceive them as colors.

- Usually referenced by wavelength in nm.
Lots of photons

- More photons = brighter light
- Photons of many different frequencies = colors blended together
Spectral power distribution

- Shows how much power is emitted by a light source for every frequency in the spectrum

Natural light

Incandescent bulbs
Fluorescent bulb

Sodium lamp (streetlight)

Warm white CFL
• Light enters through the pupil, refracts through the lens, and is projected onto the retina
Retina

- A layered assembly of nerve cells and light sensors
- Sensors (rods and cones) are actually on the back, light must pass through all other layers first
• Rods (intensity) and cones (3x color: RGB)

• Each type of cell has a spectrum that it responds to
Rods and cones

- Light to frequency converters: the more photons they absorb, the more they fire
- ~4.5 million cones, ~90 million rods
- Cones work best in bright light, rods best in dark
- Cone luminances aren’t perceptually equivalent
  - Green is the most intense (59%), then red (30%), then blue (11%)
More facts

- Cones have significantly better response time
- Both sensors can get fatigued or overloaded
  - Camera flash gives you a blind spot
  - Negative afterimage: stare at one color for too long, and you’ll be oversensitive to the opposite color
Trichromatic vision

- The 3 types of cones have overlapping response curves, meaning that several different combinations of photons can excite the same response.
- This is the foundation of RGB color: we don’t need to produce every wavelength of photon, we just need to trigger the cones in the same way.
- This breaks down when coherency matters, like wavelength-dependent refraction.
Tangent: color spaces

• RGB values are just one way to represent colors, you can transform it into other spaces

• Several other popular ones:
  • Hue, Saturation, Value (HSV)
  • Cyan, Magenta, Yellow, Black (CMYK)
RGB CUBE, HSV CYLINDER
CMYK

• Secondary colors, subtractive process, used in printing
• Can adjust the mixture for different effects
Perceptual problems

• Those color models are overly simplistic

• The color that you actually see depends on the surrounding lighting, the display characteristics of the device, and so on

• Result: \( <203, 44, 89> \) looks completely different on two different monitors, and when printed

• As a result, people have tried to create perceptual models of color that more accurately capture what you end up seeing
A bunch of detailed and tedious experiments were done in the late 20s to tell what colors can be differentiated from each other.

Came up with a mathematical model and standard that describes perceived colors.

Given a spectral distribution of photons, the model will tell you what color you will perceive.

Computes some extra parameters along the way: x, y, and z (plus brightness)
CIE XYZ
Every display device can only show a subset of the full CIE space (shown: sRGB standard)
Yet more color spaces

- There’s an enormous number of color spaces
- Some perceptually normalized (L*a*b*, sRGB, etc.)
- Some not (Chroma/luma, RGB, etc.)
- I won’t spend all lecture going over it...
Back to the eye: Light adaptation

• The retina has a dynamic range of about 100:1

• The pupil can expand and contract to adjust exposure further

• Chemical changes also take place over time (~30 minutes) when light levels change
  
  • Visual acuity shifts towards yellow in bright light, blue in low light
**Gamma correction**

- Under most conditions, perceptual response to brightness is logarithmic
- Must compensate by adjusting power with an exponential curve when displaying on a device
Retinal processing

• There’s a ton of information coming in from the color sensors, way more than goes down the optic nerve

• Significant amounts of processing and compression that happens in the retina itself

• Accomplished by several types of retinal ganglion cells
• Small neighborhoods of sensors are grouped together into “fields”

• These fields extract edge information

• Almost identical to the edge detection kernels used in image processing...
Edge hypersensitivity

- Edges are perceived very sharply; they override most other types of information in an image
• Humans are way more sensitive to edges in brightness (luminance) than color (chrominance)
• Time-delay summations happen among ganglion cells, giving you motion information
• Rods / cones / ganglion cells are not distributed uniformly

• Highest density and largest concentration of cones is in the fovea (about middle 2° of visual field)
Eye movements

• Saccades: short, quick jumps
• Vergence: both eyes fix and focus on a point
• Pursuit: smooth movements to keep a moving object on the right part of the fovea
• Vestibulo-ocular reflex: stabilize image while head is moving or rotating
Sensor distribution

- Color sensors are distributed in a spatially uniform, but radially random pattern (blue noise)
- Means we’re equally sensitive along all angles, but only at a certain resolution
Relevance to Graphics

• Just from what we know so far, there are several useful pieces of information for graphics

• To sum up the punchlines...
Summary: Color

- We can represent color as RGB triples
- Perceptual mapping is important for accurate color reproduction
- The eye uses a few different brightness scaling methods to adjust for lighting conditions
- No device can display all visible colors, and they have very poor dynamic range
- RGB assumption breaks down if you do any wavelength-dependent effects
Summary: Edges

- Humans are ridiculously sensitive to edges
- Edge detection starts in the retina
- Given that we have a limited number of pixels to work with, CG tends to generate too many edges
  - Smoothing this out is what anti-aliasing is for
- Can store / draw chroma at much lower resolution than luma
Summary: Motion

- Motion is as strong a signal as edges, if not more
- Also starts in the retina, with time-delay correspondences between ganglion cells
- Inadvertent motions in CG (jaggies, crawlies, numerical imprecision) are distracting, and must be addressed
Summary: Visual Resolution

- Your best visual acuity is in a 2° cone in the middle of your field of view (fovea)
- Everything outside of that is bad or worse
- The eye uses several motion strategies to get the right part of the image into the fovea
- Everything else is just filled in by guessing later
Summary: Blue Noise

• Sampling pattern of fovea is evenly distributed spatially but uniformly distributed radially (blue noise)

• Visual noise that fits this pattern will be practically invisible, since it’s the noise your visual system automatically filters out

• If you must have errors in your images, try to make it blue noise!
But wait...

- We haven’t even started the visual cortex yet
- Color theory, object recognition, pattern recognition, spatial cues, lighting cues, etc...
- Take a sensation and perception class
Figures courtesy...

- Wikipedia [WP]
- GE light spectral profiles [GE]
- Yvon Delville’s Sensory and Behavioral Neuroscience course notes, UT Austin [YD]