**Source to Detector**
- Light Source—spectrum
- Path to illuminated object
- Reflection from object—reflectivity
- Path to Cornea
- Focusing to two-dimensional spatial map of object on retina

**What arrives on retina 1?**
- Light is Electromagnetic Wave
- EM waves have speed, frequency, wavelength $c = f \lambda$.
- $\mathbf{E}$ and $\mathbf{B}$ are transverse to direction
- Time variation of each recreates the other advanced forward in location
- Passage of oscillating $\mathbf{E}$ shakes electrons found along the path

**What arrives on retina 2?**
- Light interacts in discrete energy bundles, known as quanta, or photons
- The energy in one photon is determined by the frequency of the wave $E = hf$, where $h$ is Planck’s Constant

**Visible Light**
- Speed $3 \times 10^8$ meters/s (very fast)
- Wavelengths ~ 400-700 nanometers (violet to red)
- Frequencies so high that electrons are about the only thing able to shake that fast (to create the light in the first place)
- Photon energies ~ 2 to 3 electron Volts (nice size for instigating chemical reactions)
What Happens at Retina 1?
- Photons absorbed by pigments in sensing cells (rods or cones) cause associated nerves to fire.
- Rods are mainly useful in vision at very low light levels—role in color vision (which requires bright light) is small.
- Three types of cones with different pigment sensitivity functions (short S, middle M, and long L wavelength sensitive versions).

Cone Sensitivity Functions
- Short, Medium, and Long λ.
- Med and Long very similar (recent evolutionary distinction).
- Red-Green color blindness missing one of L, M.

Monkey Story
- > 50 Myr ago: “Old World” apes only, 2 receptors only (S, ML).
- ~35 Myr ago: Some OWA migrated to “New World”—their descendants remain today, 2 receptors only.
- Next: LM receptor on X chromosome of OWA duplicates and one copy mutates slightly—three receptors on some OWAs (S,M,L).
- Three receptor version propagates through OWA population, likely with significant advantage (as brain had to change to use it). (e.g. finding red berries in green foliage).
- Humans arose from OWAs. To this day, 7% of males (having only one X chromosome) still have only one LM receptor type. Most females with two X chromosomes manage to avoid the corresponding R-G color blindness.
Cross Talk in the Eye

- The firing rates of the three types of cones, at each position on the retina is NOT the information passed on to the brain for assembling and interpreting the image (or sequence of images).
- A lot of processing occurs in the eye, combining signals from different cone types and different locations.
- Hard-wired processing, for identifying objects (via their edges and colors), measuring their motion, etc.
- Red-Green color discrimination improved by recording (weighted) difference between L and M cone responses.
- Complementary colors provide clues to combinations--color opposites. (After-images.)

Aside on Edges

- Edges (in brightness or color) are easily found by combining the brightness at each location with the negative of the average brightness (of the same or a different color channel) in a slightly larger area.
- This form may also be useful in pattern recognition

Trichromatic Model of Color Sensation

- Three channels, loosely R, G, B
- Sum of three gives a measure of total intensity of light
- Fractions of total in any two channels determined perceived color

Example: 3 Incident Spectra

- Bluish, Even, and Redish distributions of light arriving on cones
- "perceived color" is determined by location in horseshoe
- Intense color near boundary: pale near white spot
Problems w Trichromatic Model

- Another dimension—what are brown, olive, and other colors not found in the rainbow?
- How is it that we can correctly identify the colors of objects in a scene when the color of the illuminating light varies enormously? (color constancy)

Three Dimensionality

- Brown is dim orange with a bright surround

Color Constancy

- Scene includes a mixture of objects with different intrinsic “colors” and brightnesses.
- Color of illuminating source changes

Example

- 3 retinal receptor channels (R, G, B)
- 3 objects with different reflectivities, peaking in red, green, blue
- 1 white object
- 3 light sources (used one at a time), one blueish, one greenish (or evenish), one redish
**Example Characteristics**

- Assumed Illuminations
  - 0
  - 0.2
  - 0.4
  - 0.6
  - 0.8
  - 1
  - 1.2
  - 400 450 500 550 600 650 700
  - Wavelength (nanometers)
  - Blueish
  - Even
  - Redish

- Assumed Object Reflectivities
  - 0
  - 0.2
  - 0.4
  - 0.6
  - 0.8
  - 1
  - 1.2
  - 400 450 500 550 600 650 700
  - Wavelength (nanometers)
  - 475
  - 550
  - 625

- Linear Combinations of L, M, S
  - Response 1.9L - 1.4M + 0.4S
  - 0.8L + 0.25M
  - 1.8*S

- Local Fraction - Fraction
  - 0
  - 0.25
  - 0.5
  - 0.75
  - 1
  - F(red)
  - F(green)
  - 650
  - 525
  - 475
  - Blueish
  - Evenish
  - Redish

**Results 1**

- One colored line for each object
- Clockwise trajectory as light changes from blue to red
- Circles show average color
- Crosses show color of light reflected from white surface

**Perceived Color**

- Both reflection from white and average of all reflected light give good indication of color of illumination
- Use to correct from fraction-fraction color to perceived color, a relatively constant quantity for an object as lighting is altered.

**Red light**

- Red light on blue object or blue light on green object

**Green light**

- Red light
  - 0
  - 0.25
  - 0.5
  - 0.75
  - 1
  - F(red)
  - F(green)
  - Red obj
  - Green obj
  - Blue obj
  - All obj - red light
  - B obj - wt light
  - G obj - wt light
  - R obj - wt light

**Blue light**

- Blue light
  - 0
  - 0.25
  - 0.5
  - 0.75
  - 1
  - F(red)
  - F(green)
  - Red obj
  - Green obj
  - Blue obj
  - All obj - blue light
  - B obj - wt light
  - G obj - wt light
  - R obj - wt light
Misc
- http://photo.net/photo/edscott/spectsel.htm#01
- Search on "color vision", "chromaticity diagram", "color constancy", . . .
- Playing with color

Possible demos
- Spectrum of projector lamp
- 3 projectors with filters