

## Two Ways to Mix Red, Green, and Blue Light

1. Additive Color Mixing  
• Mixing "Lights"

➔ 2. Subtractive Color Mixing  
• Mixing "Pigments"

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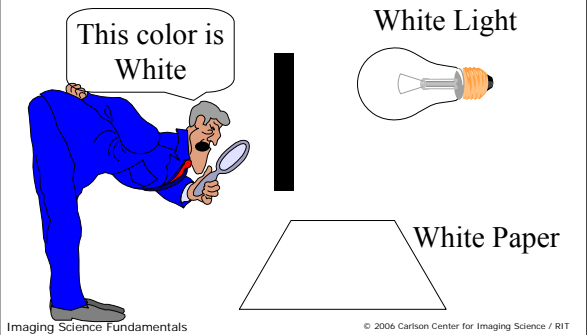
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## Subtractive Color Mixing Starts with White (R+G+B)



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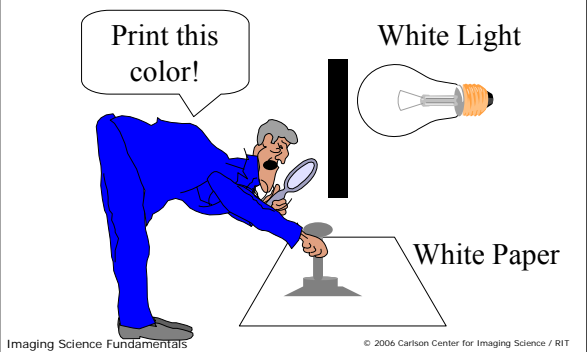
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## Add Light Absorber (Pigment or Ink)



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### Ink Absorbs (Subtracts) Light from White

This color is gray

White Light

"Gray" absorbs equal amounts of all wavelengths

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### Subtractive Color Mixing Starts with White Light

Magenta ink absorbs Green Light

White Light

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### Spectrum of White Light

Intensity

400 Wavelength in nm 700

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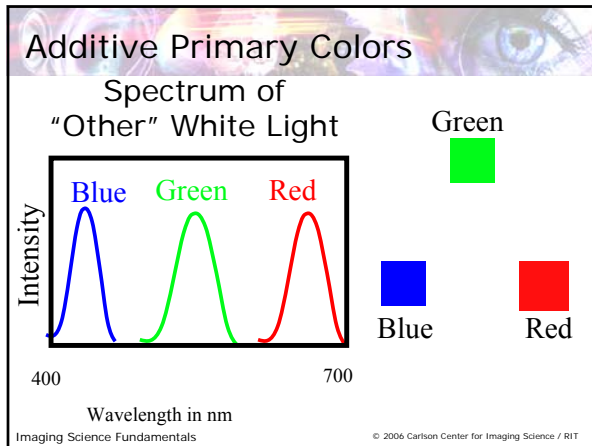
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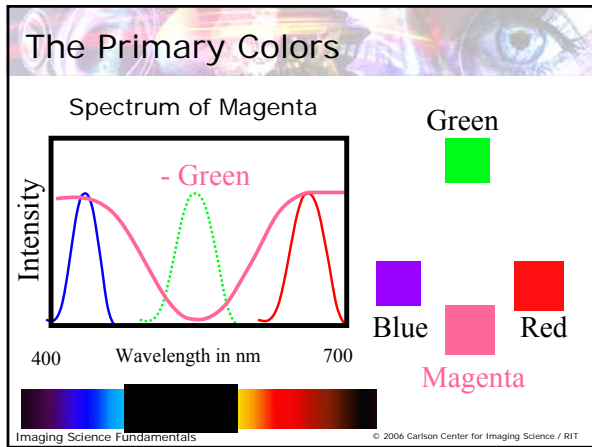
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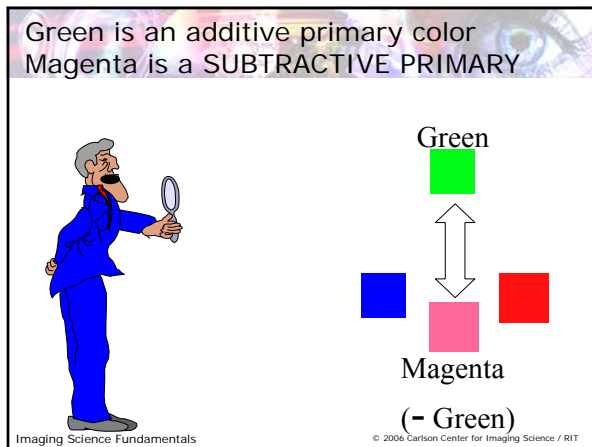
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### Subtractive Color Mixing: Start with White

Cyan ink absorbs Red Light

White Light

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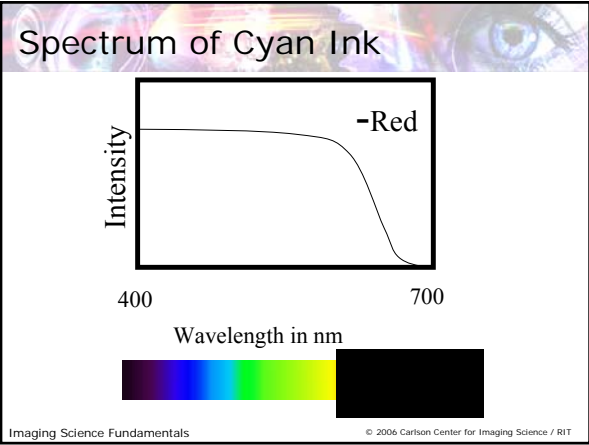
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### Red is an Additive Primary Cyan is a SUBTRACTIVE PRIMARY

Cyan

Red

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### Yellow Ink Absorbs Blue Light

Yellow ink absorbs Blue Light

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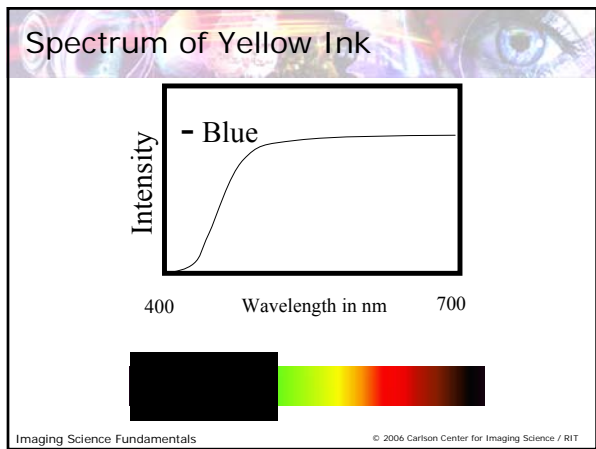
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### Blue is Additive Primary Yellow is SUBTRACTIVE PRIMARY

Blue Yellow

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**"Additive Primary Colors"**  
Red, Green, Blue

Green

Blue

Red

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**"Subtractive Primary Colors"**  
Cyan, Magenta, Yellow

Cyan (- Red)

Yellow (- Blue)

Magenta (- Green)

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**Lay-Person's Names for Crayon Colors**  
"Blue, Red, Yellow"

~~Cyan~~ "Blue"

Yellow

~~Magenta~~ "Red"

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Mixture of Cyan and Yellow

This color is Green

White Light

Subtract red, blue

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Mixture of Magenta and Yellow

This color is Red

White Light

Subtract green, blue

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Mixture of Magenta and Cyan

This color is Blue

White Light

Subtract green, red

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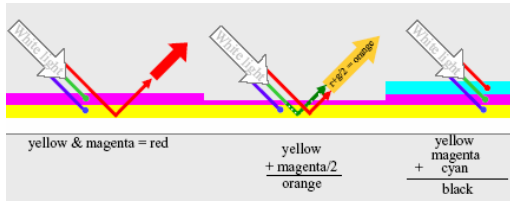
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## Other Colors by Varying Amount of Colorant in Each Layer



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## Subtractive color reproduction

Printers use 4 colors: cyan, magenta, yellow, black  
Improves detail, saves money on more expensive CMY colorants



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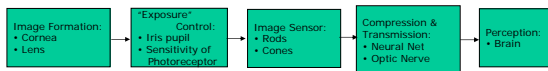
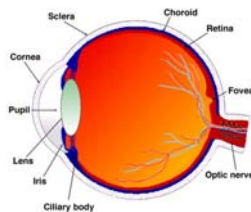
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## Human Visual System



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## Visual Experience Includes:

- brightness
- color
- form
- texture
- depth
- transparency
- motion
- ...

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## We'll review:

- Anatomy of human eye
- Image formation by human eye
- Method of light detection
- Retinal processing
- Optical defects and diseases

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## Eye

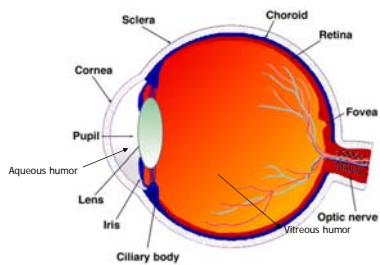


Fig. 6. Vertical sagittal section of the adult human eye.  
[www.hunkeler.com](http://www.hunkeler.com)

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## Eye is a "Jelly-Like" Mass

1. **Sclera:** white, opaque, and tough flexible outer shell
2. **Cornea:** transparent and convex outer part, curve is somewhat flattened to reduce spherical aberrations (deviation from ideal lens), first optical element of system, refractive index  $n = 1.376$
3. **Aqueous Humor:** Medium between cornea and lens, refractive index  $n = 1.336$
4. **Iris:** aperture diaphragm that controls the amount of light entering the eye, circular and radial muscles, diameter from approximately 2 to 8 mm
5. **Lens:** biconvex crystalline, like an onion ( $\approx 22,000$  layers), about size of M&M (9 mm diameter, variable thickness of about 4 mm), refractive index varies from center to edge ( $1.336 < n_{\text{lens}} < 1.406$ ), absorbs about 8% of visible spectrum
6. **Vitreous Humor:** supports the eyeball,  $n = 1.336$
7. **Choroid:** dark layer, absorbs stray light like black paint in camera
8. **Retina:** thin layer of receptor cells, covers inner surface of choroid, **rods** and **cones**, uses a photochemical reaction to convert light to nerve impulses

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## Color Sensors in Retina

- $\approx 6$ -7 million cones, located in the **fovea** (central portion of retina), three different colors, each cone in fovea connected to own nerve  $\Rightarrow$  can resolve fine detail.
- Cone vision is called **photopic**, at normal daylight levels, high resolution.
- Muscles rotate eyeball until image falls on fovea
  - cones give color and high resolution
  - Image kept stationary on given spot of photoreceptors would fade due to deterioration of photochemical response
  - Without fovea the eye would lose 90% of its capability, retaining only peripheral vision.
- Normal human vision over  $390 \text{ nm} \leq \lambda \leq 780 \text{ nm}$ 
  - short-wavelength limit due to crystalline lens

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## "Black & White" Vision

- Receptors are **Rods**
  - 75 to 150 million distributed over retinal surface
  - Several rods are connected to one nerve end
  - Reduces amount of detail
- Provide general overall picture of field of view
- Sensitive to low levels of illumination
- Objects that appear brightly colored in daylight appear colorless in dim light because only rods are stimulated
- Rod vision is called **scotopic**
  
- No receptors in the region where optic nerve exists the eyeball: **blind spot**.

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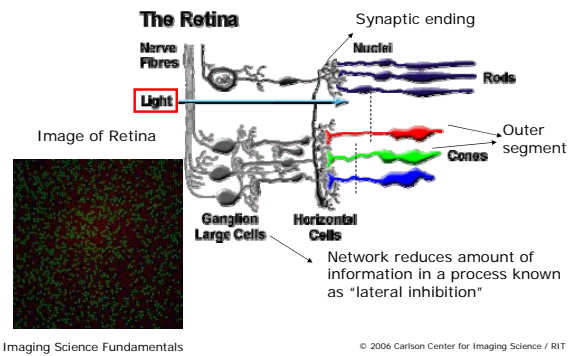
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## Neural Network in Retina




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## Neural Net and Compression

- Neural net "reorganizes" image information and discards some data
- Allows data to be transmitted to brain over limited channel
  - "narrow pipe"
- May create "confusion" between perception and reality
  - e.g., optical illusions

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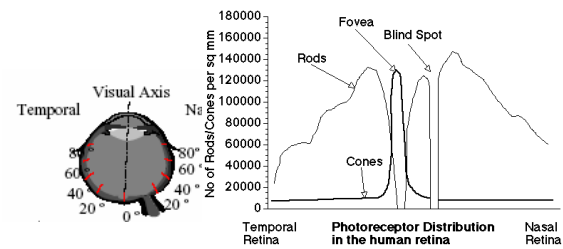
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## Distribution of photoreceptors



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## Blind spot



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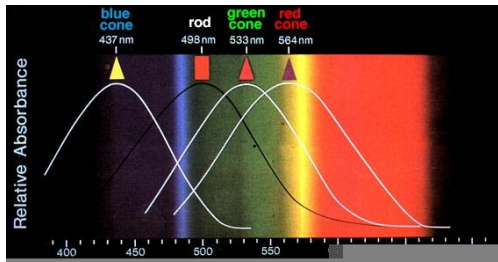
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## Response to color



[www.cquest.utoronto.ca/.../photoreceptors.html](http://www.cquest.utoronto.ca/.../photoreceptors.html)

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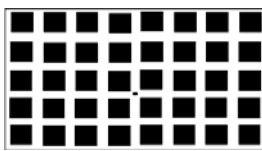
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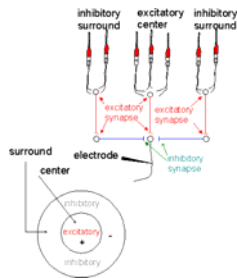
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## Lateral Inhibition of Retinal Signal



Hermann grid



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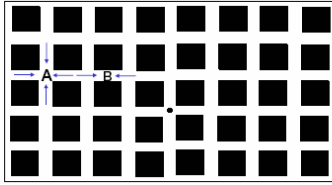
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## Lateral Inhibition Demonstrated by Hermann Grid



Region "A" Appears Darker than Region "B"  
Because 4 Inhibitory Inputs at "A" vs. 2 at "B"

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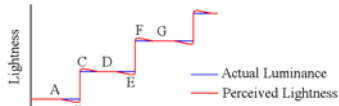
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## Mach bands = Edge Enhancement



- Intrinsic "Sharpening" in Eye Processing
- Eye "Sharpens" Edges Automatically



[www.luc.edu/faculty/asutter/MachB2.html](http://www.luc.edu/faculty/asutter/MachB2.html)

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