Color and Perception

Why Should We Care?

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- what we render is **not** what we see

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Some errors (**artifacts**) more noticeable than others

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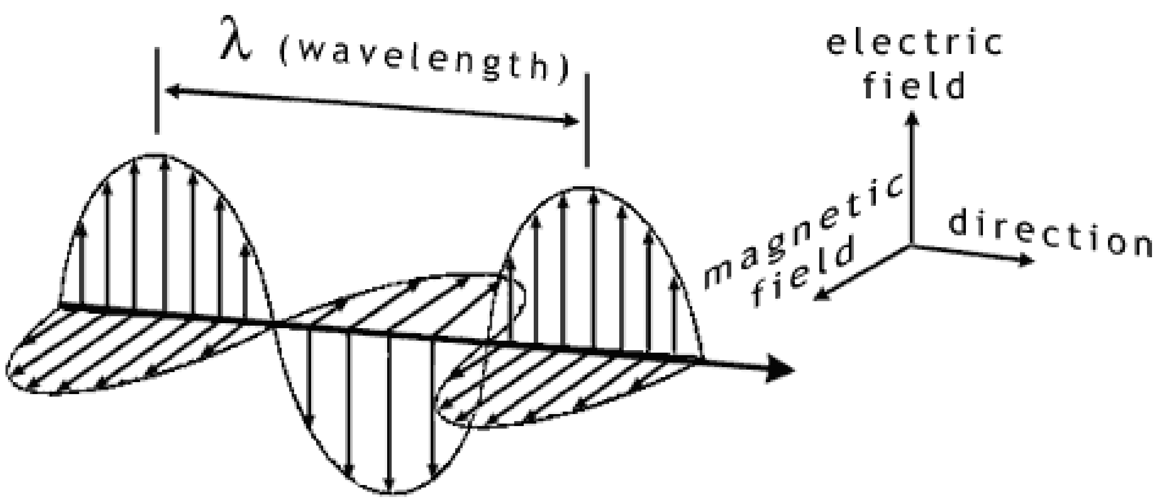
Understand vision to minimize artifacts

Light

Light exhibits **particle/wave duality**:

- stream of photons with energy E
- light wave with wavelength λ



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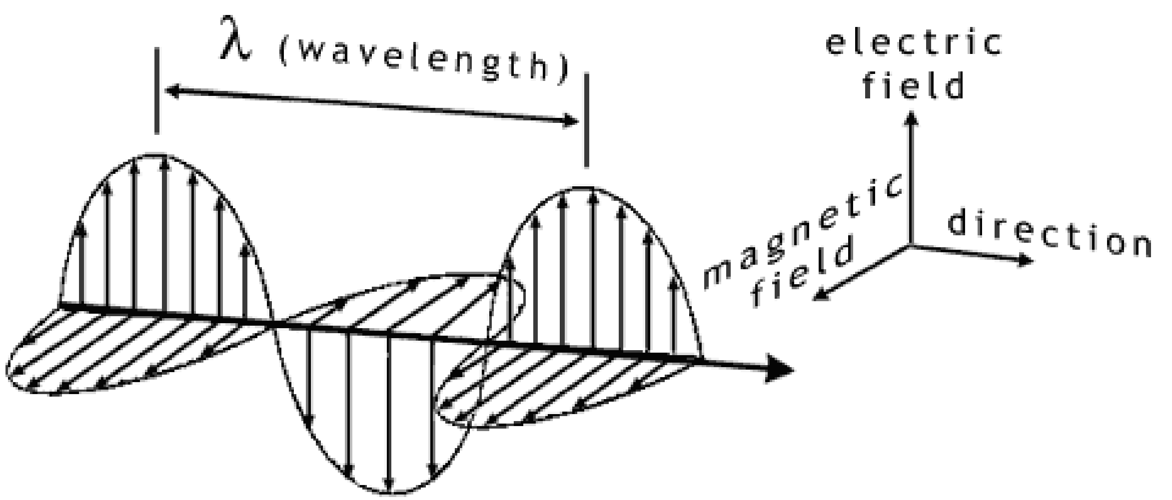

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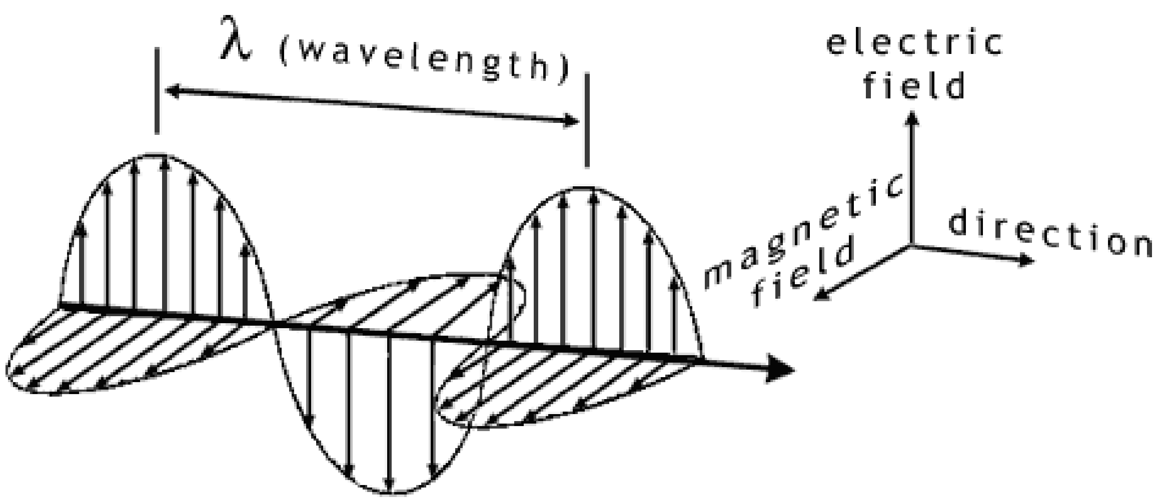
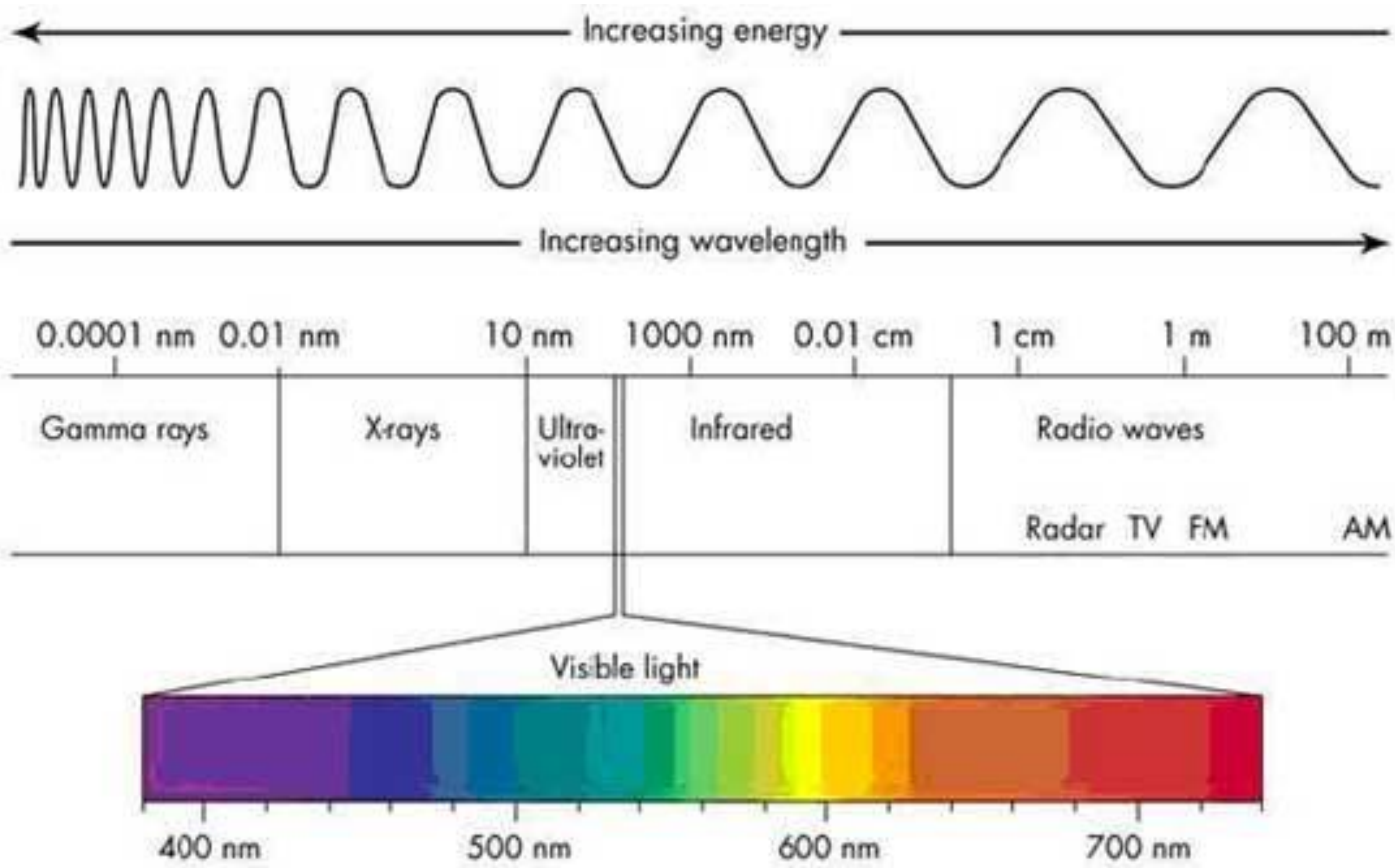


relationship:

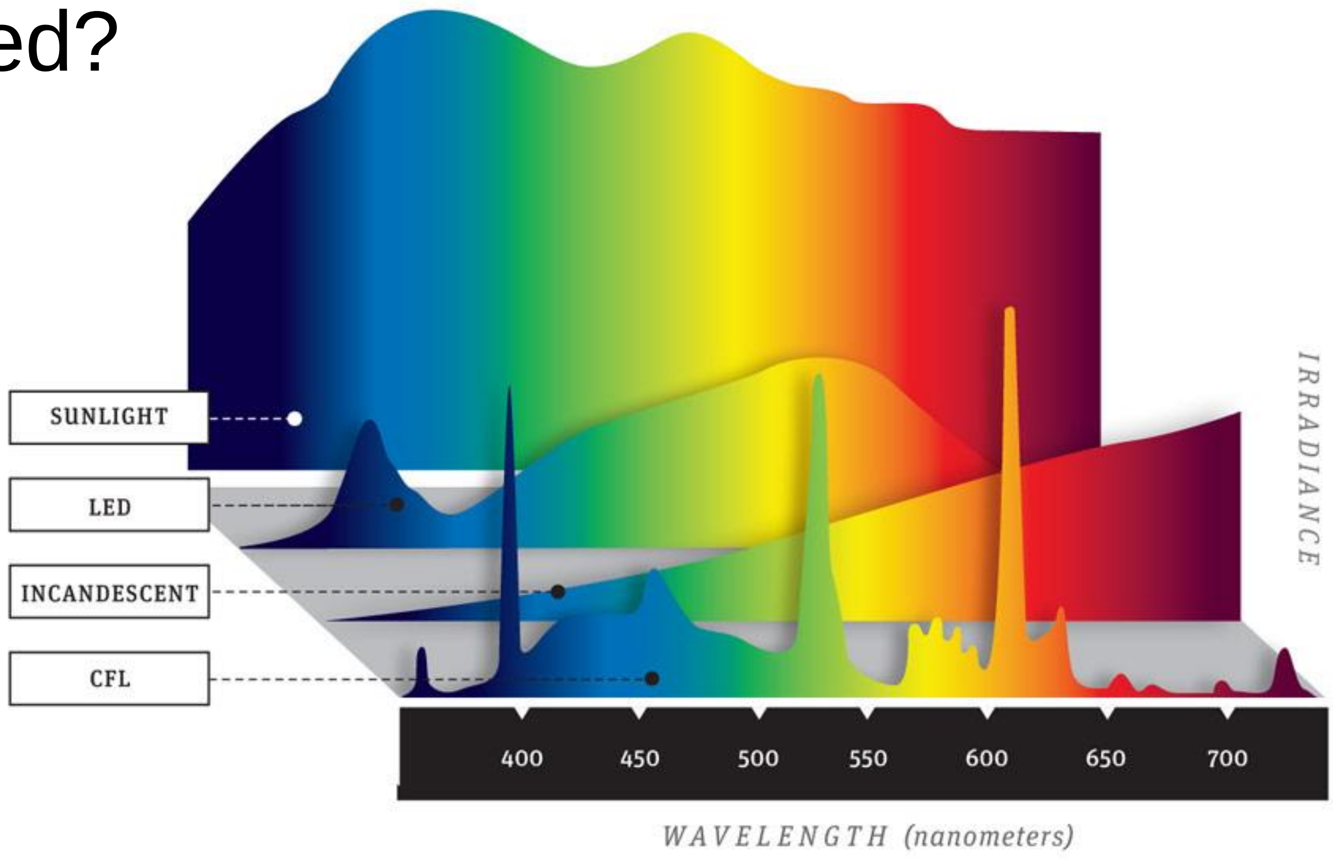
$$E = c/\lambda$$

Visible Light

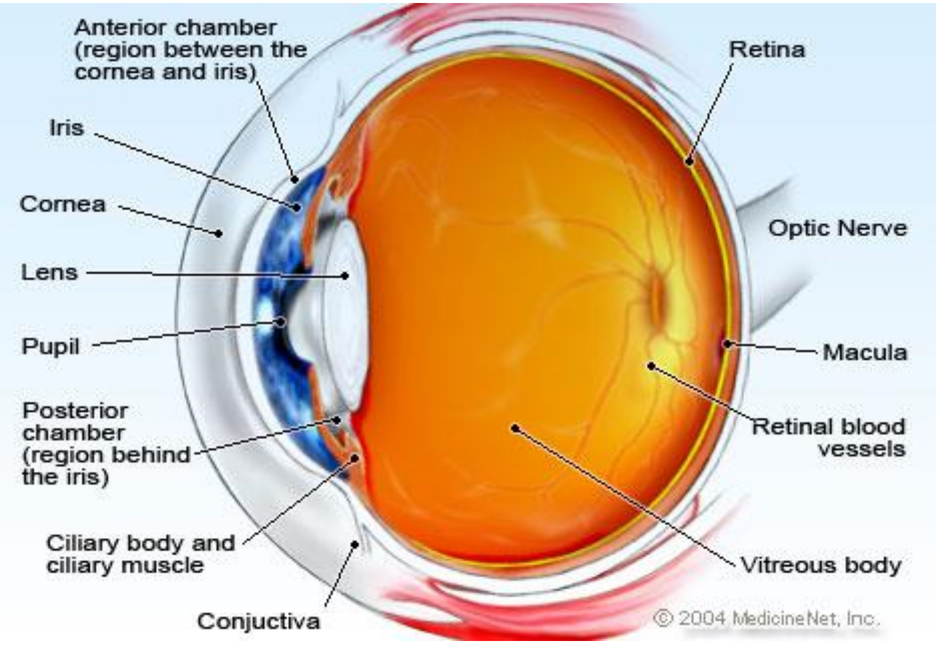


Spectral Power Distribution

How many photons of which wavelength emitted?

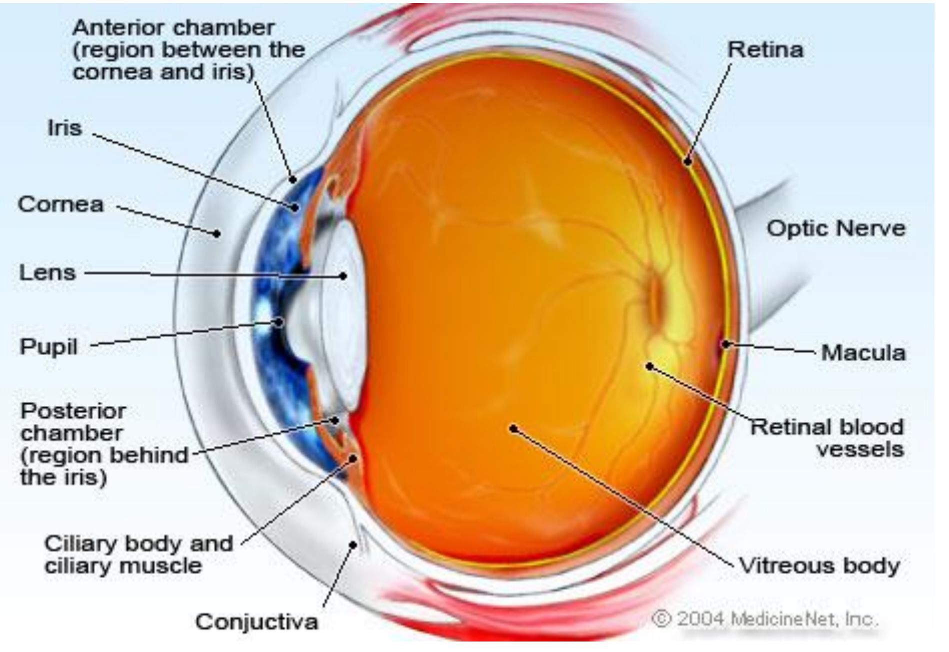


The Eye



Eye enters pupil, focused by lens, strikes retina (back of eye)

The Eye



Eye enters pupil, focused by lens, strikes retina (back of eye)

We see **blend of photons** that hit retina

Retina

Two sensors in retina.

- **cones** (4.5 million)
  - three kinds (red, green, blue)
  - work best in bright light

Retina

Two sensors in retina.

- **cones** (4.5 million)
  - three kinds (red, green, blue)
  - work best in bright light
- **rods** (11 million)
  - monochrome
  - work in dim light

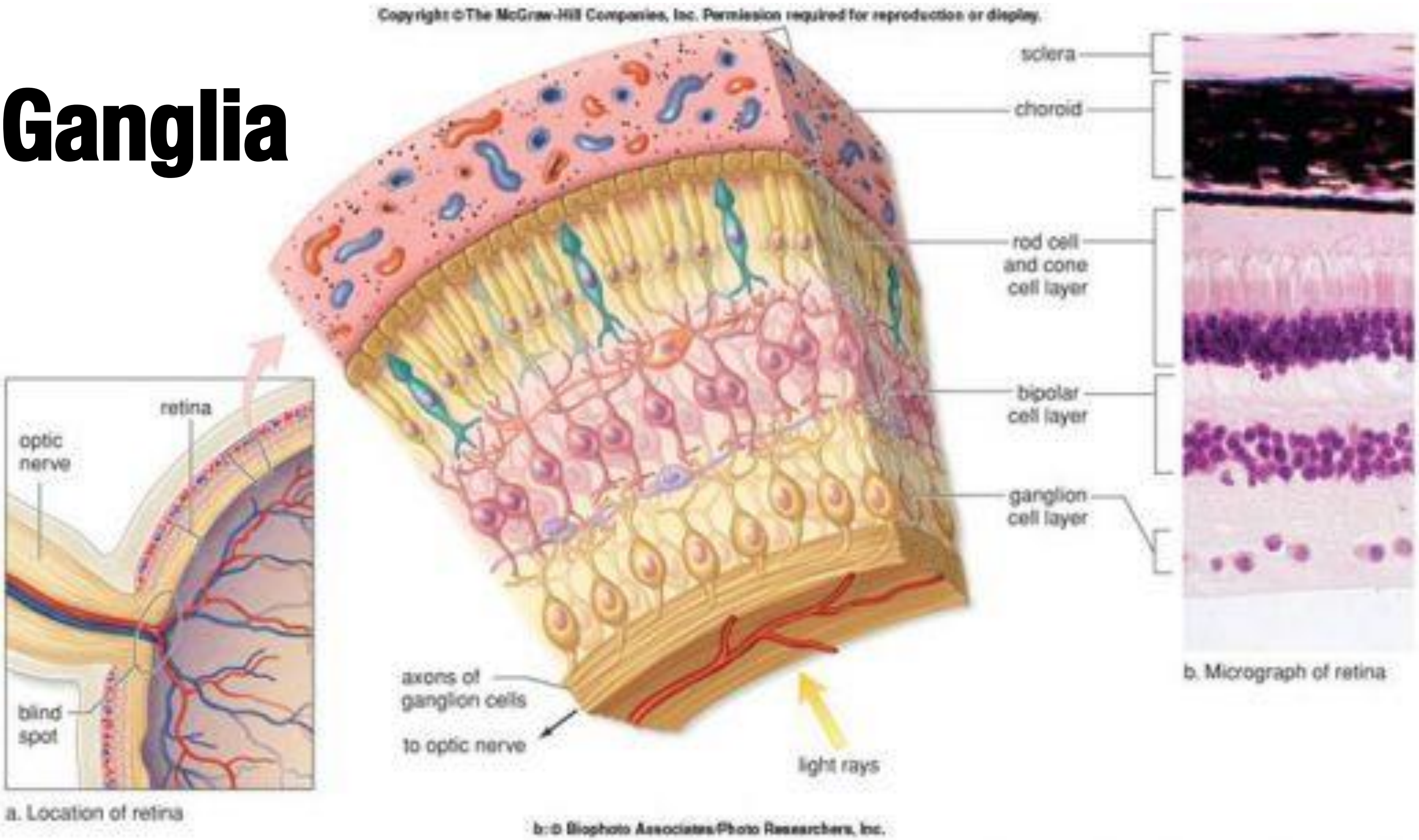
Ganglia

Connect rods & cones to optic nerve

- (optic nerve sends signal to brain)

Perform blending of signals, and some other preprocessing

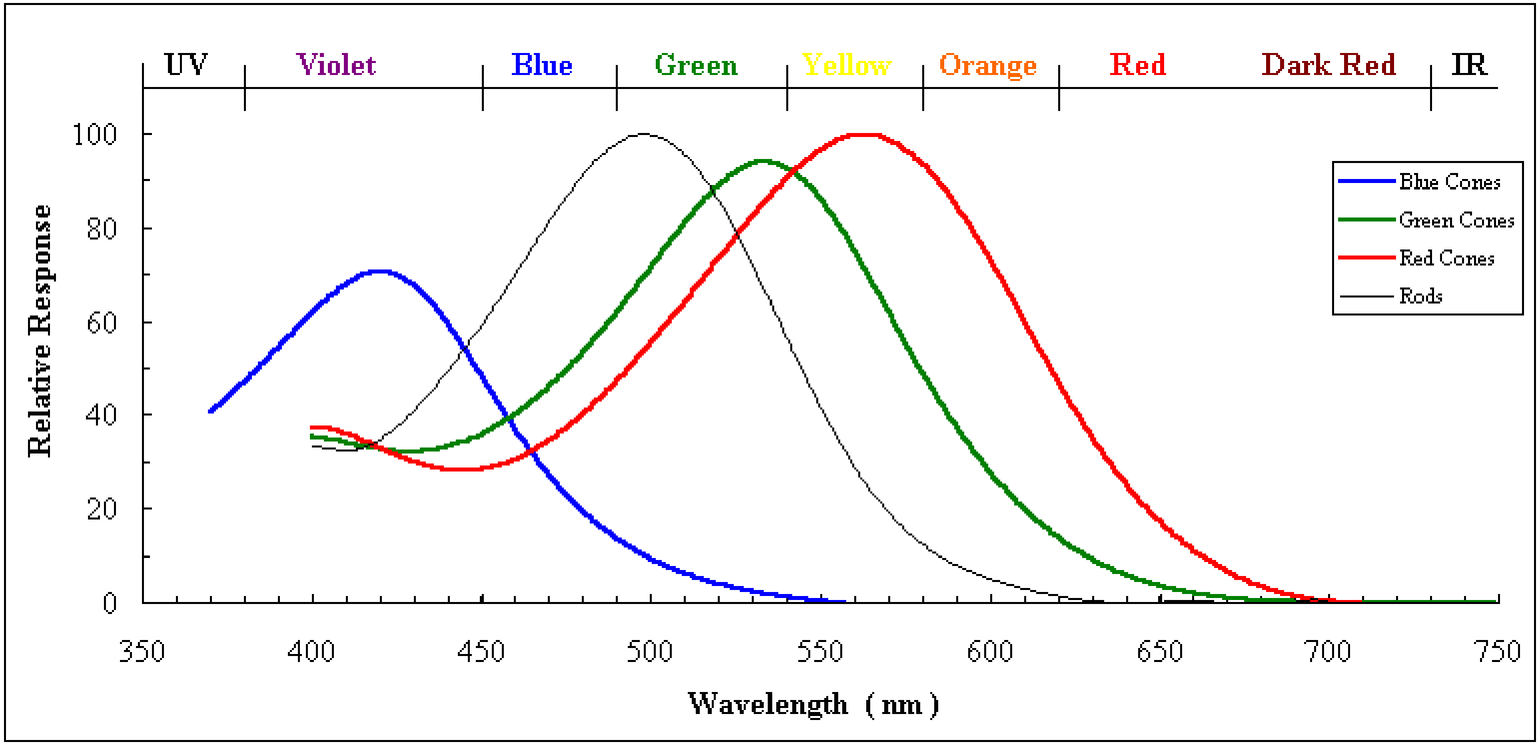
Ganglia



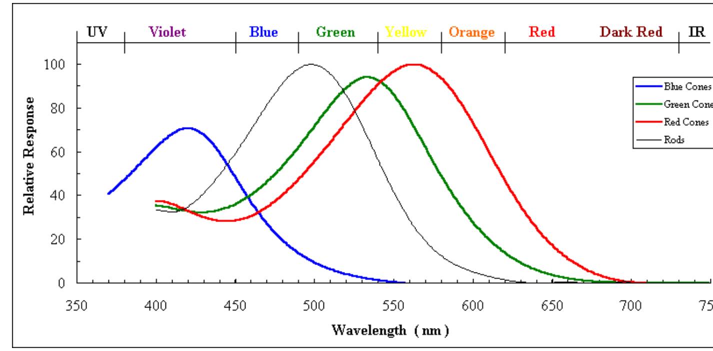
Eye is **inside-out**!

Trichromatic Vision

Each cone responds to different wavelengths



Trichromatic Vision

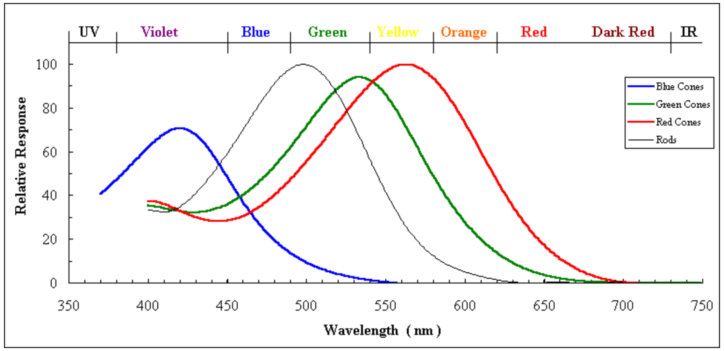


Each cone responds to different wavelengths

Key Point: many combinations of wavelengths **look** the same

- red & yellow blend == “pure” orange

Trichromatic Vision



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Key Point: many combinations of wavelengths **look** the same

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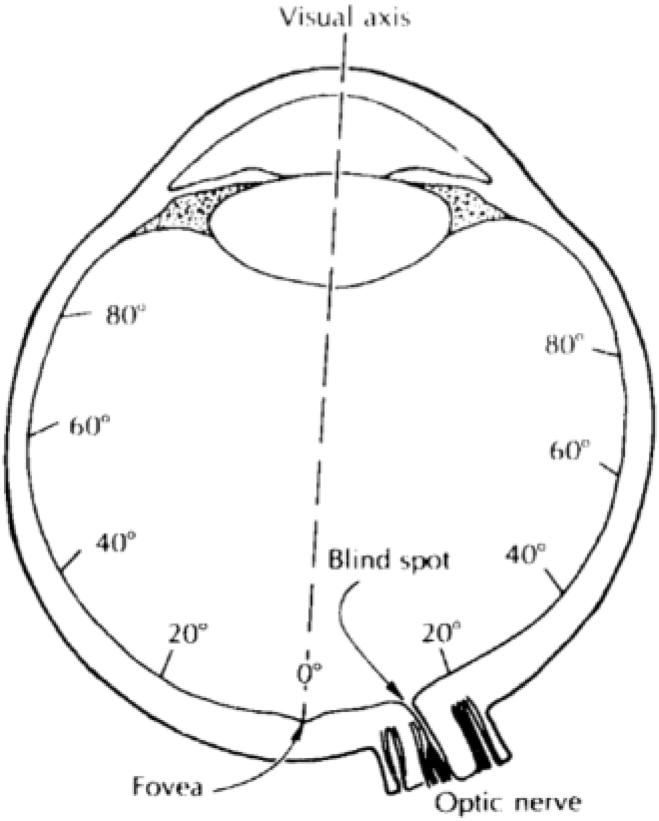
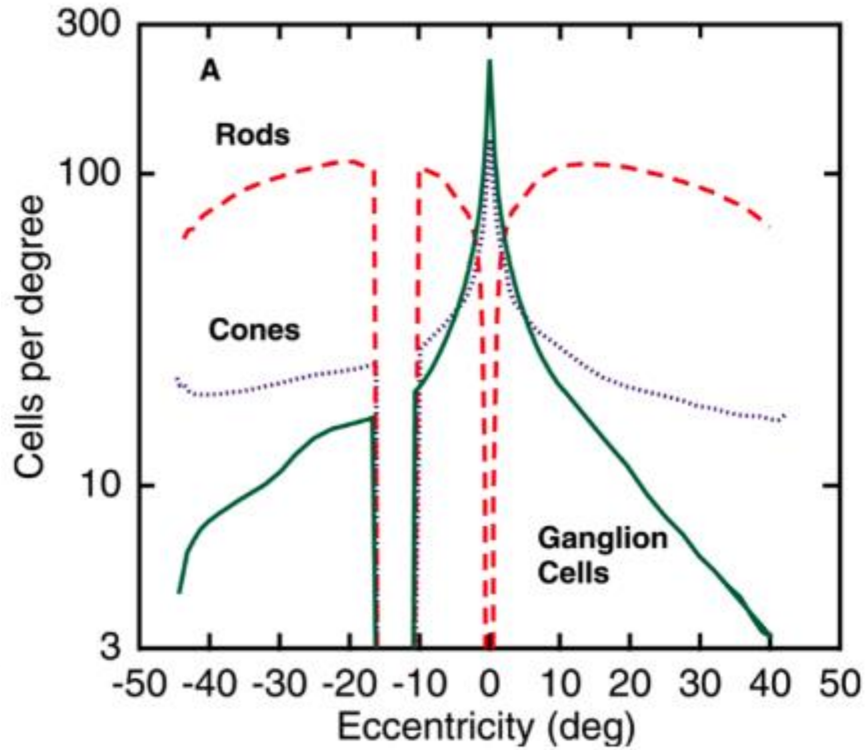
Basis of color displays, print dithering, …

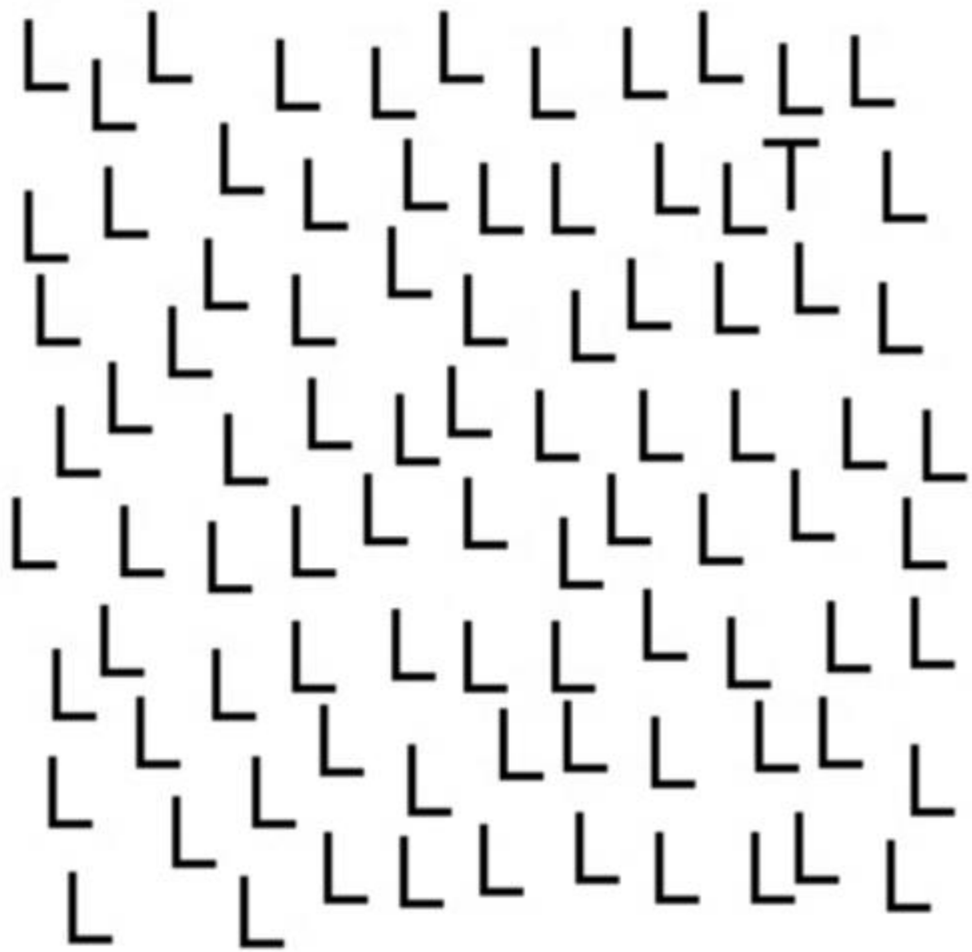
Retinal Density



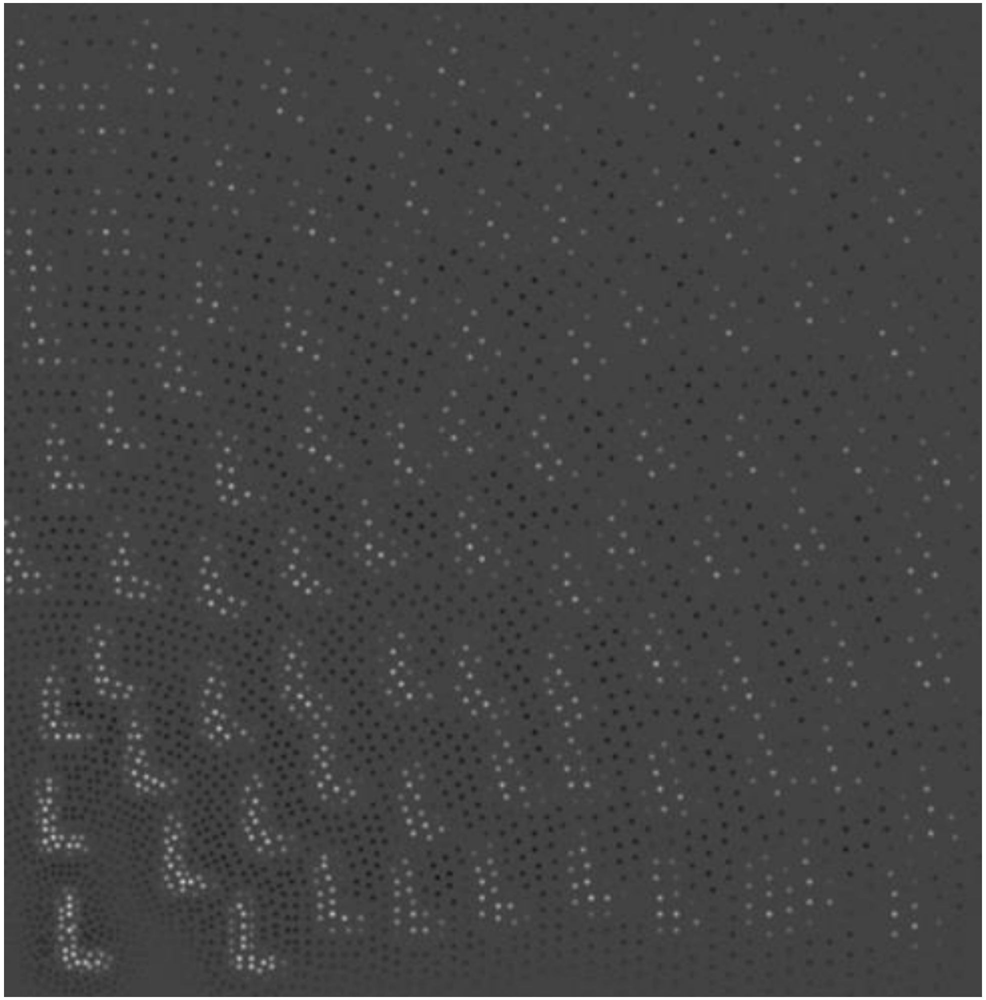


Visual acuity drops off past two degrees

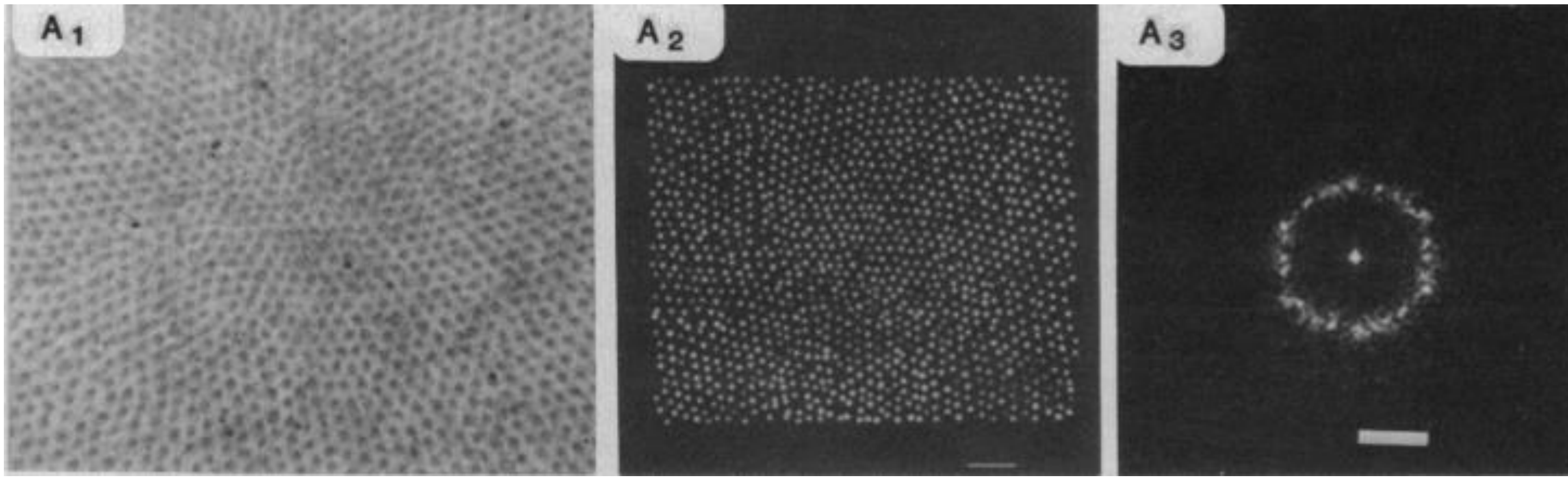
Retinal Density



What Do We See?



Sensor Distribution



Random, but **isotropic**

- “same in all directions”

This randomness called **blue noise**

Retinal Density: How We Deal

Saccades: short, quick jumps

Vergence: both eyes focus on a point

Pursuit: follow moving objects

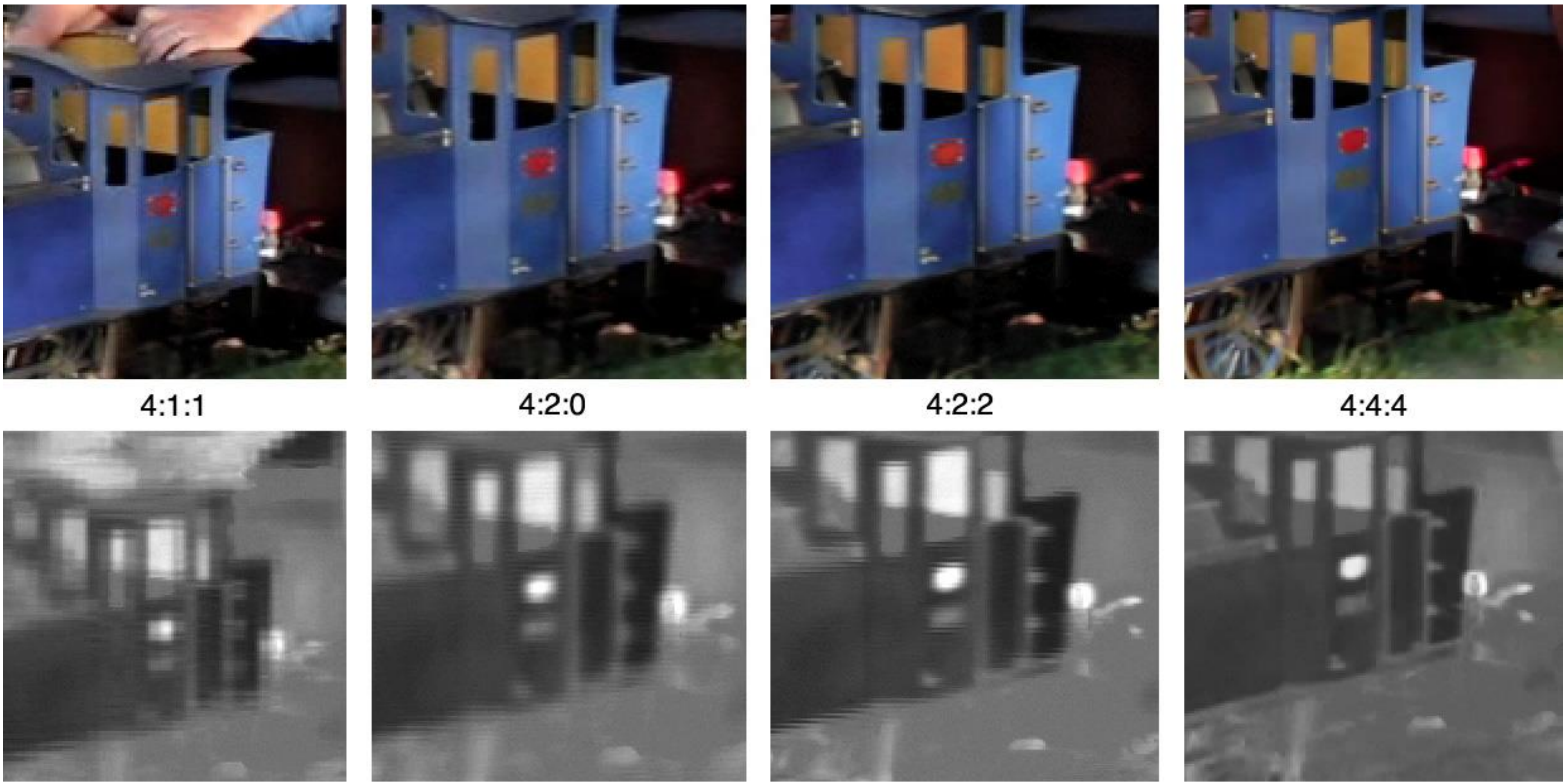
Vestibulo-ocular reflex: compensate for head motion

Chroma and Luma

luminance = “brightness”

chrominance = “color”

Eye Much More Luma-Sensitive



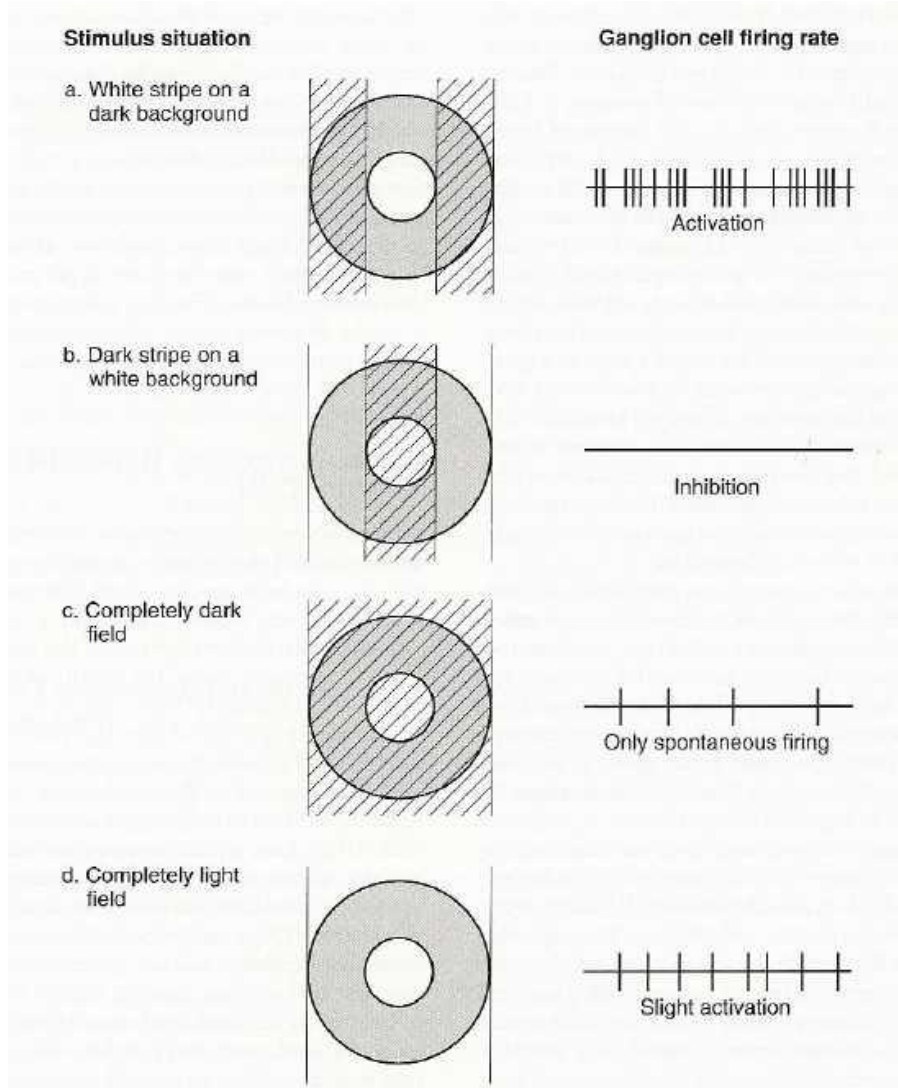
Ganglion Function

Ganglia perform some processing **before signal goes to brain**

Basically a convolutional neural network…

Ganglion Function

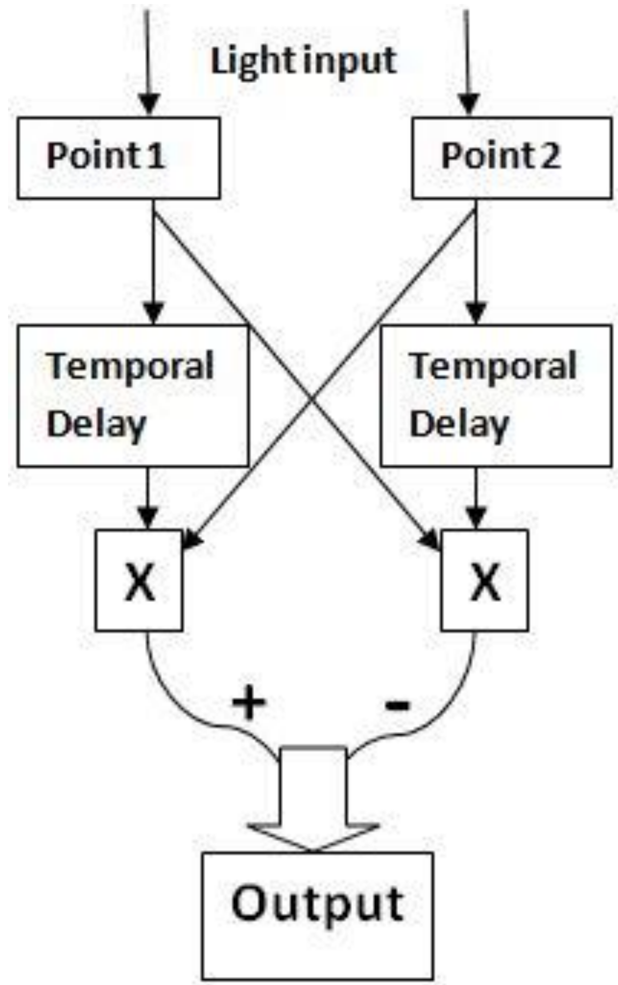
Edge detection



Ganglion Function

Edge detection

Motion detection



Ganglion Function

Edge detection

Motion detection

Punchlines:

- spurious lines are very noticeable

Ganglion Function

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  - aliasing and tearing

Ganglion Function

Edge detection

Motion detection

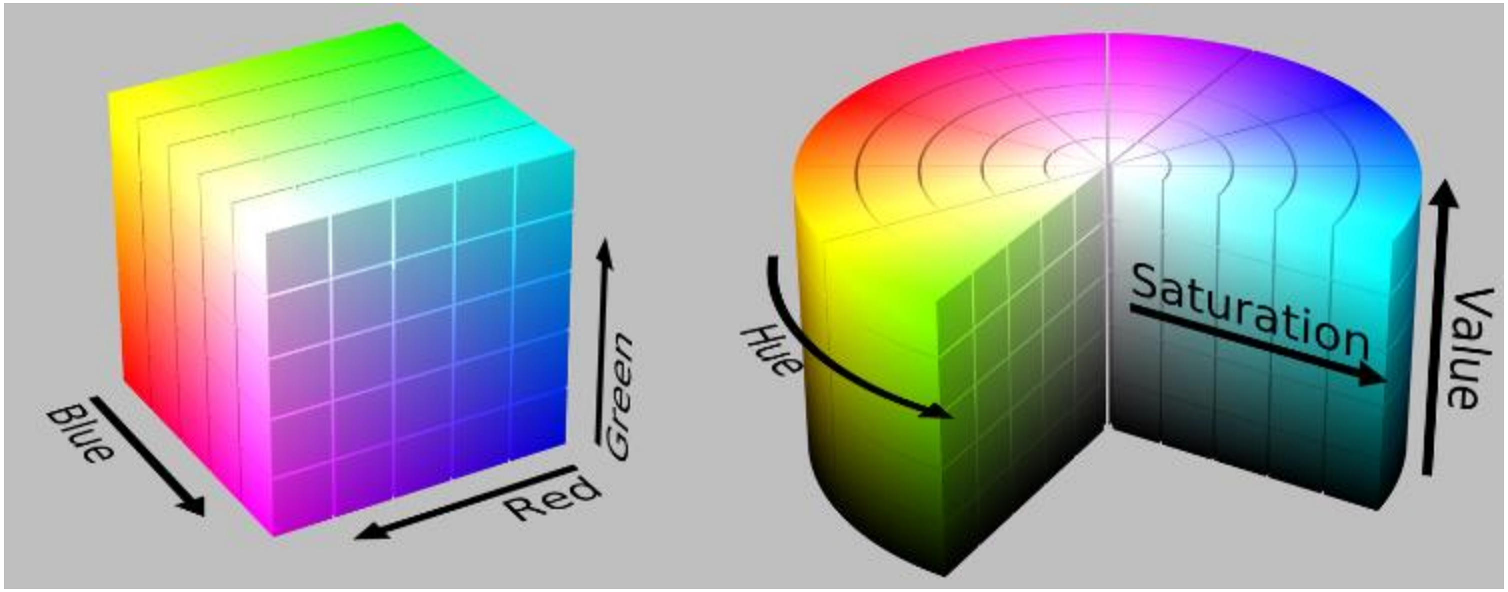
Punchlines:

- spurious lines are very noticeable
    - aliasing and tearing
- spurious motion (popping) noticeable

Color Spaces

Many ways to encode color

- RGB, HSV, CMYK most common



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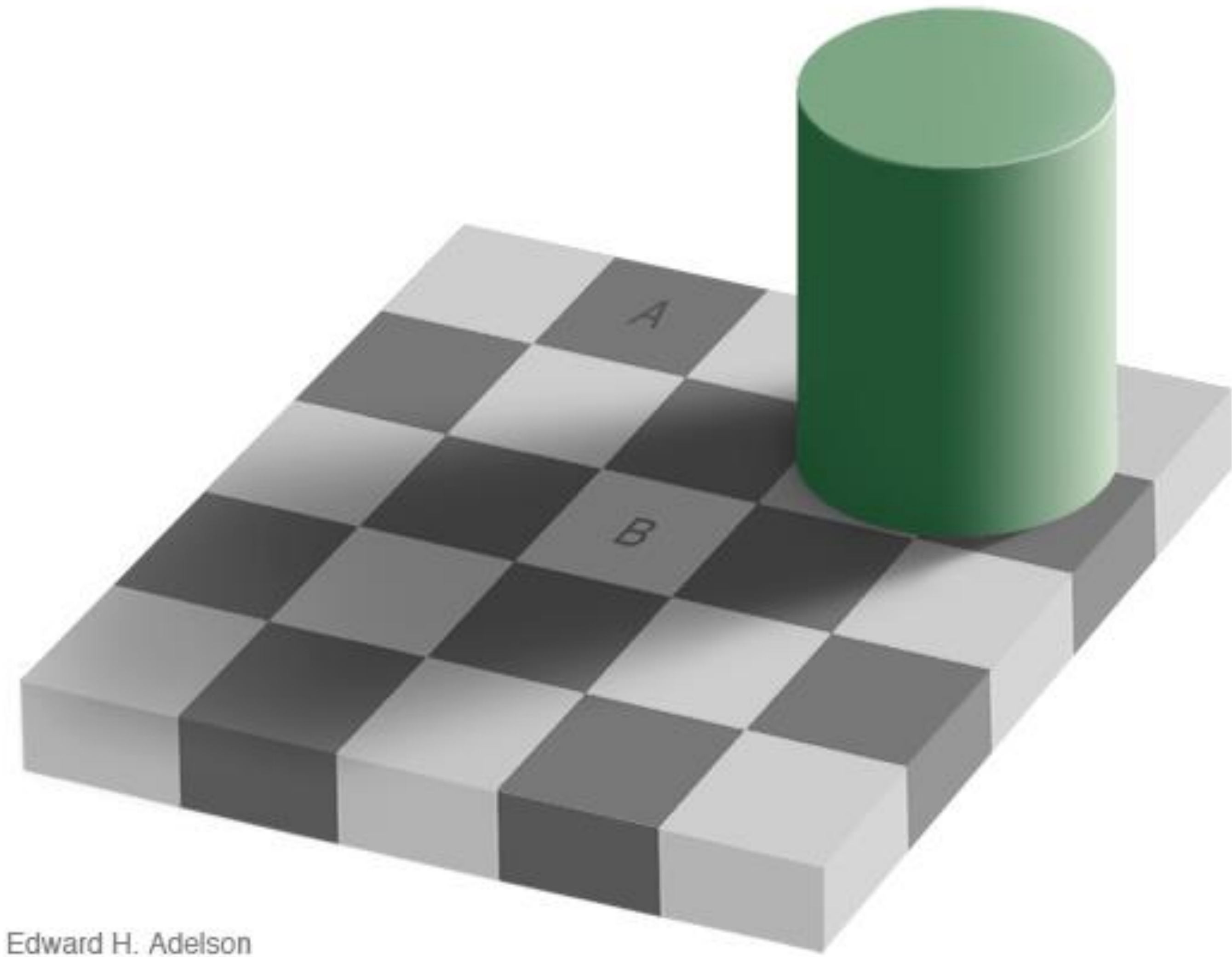
Very tenuous relationship between these color spaces and what we **actually** see

Adelson Illusion



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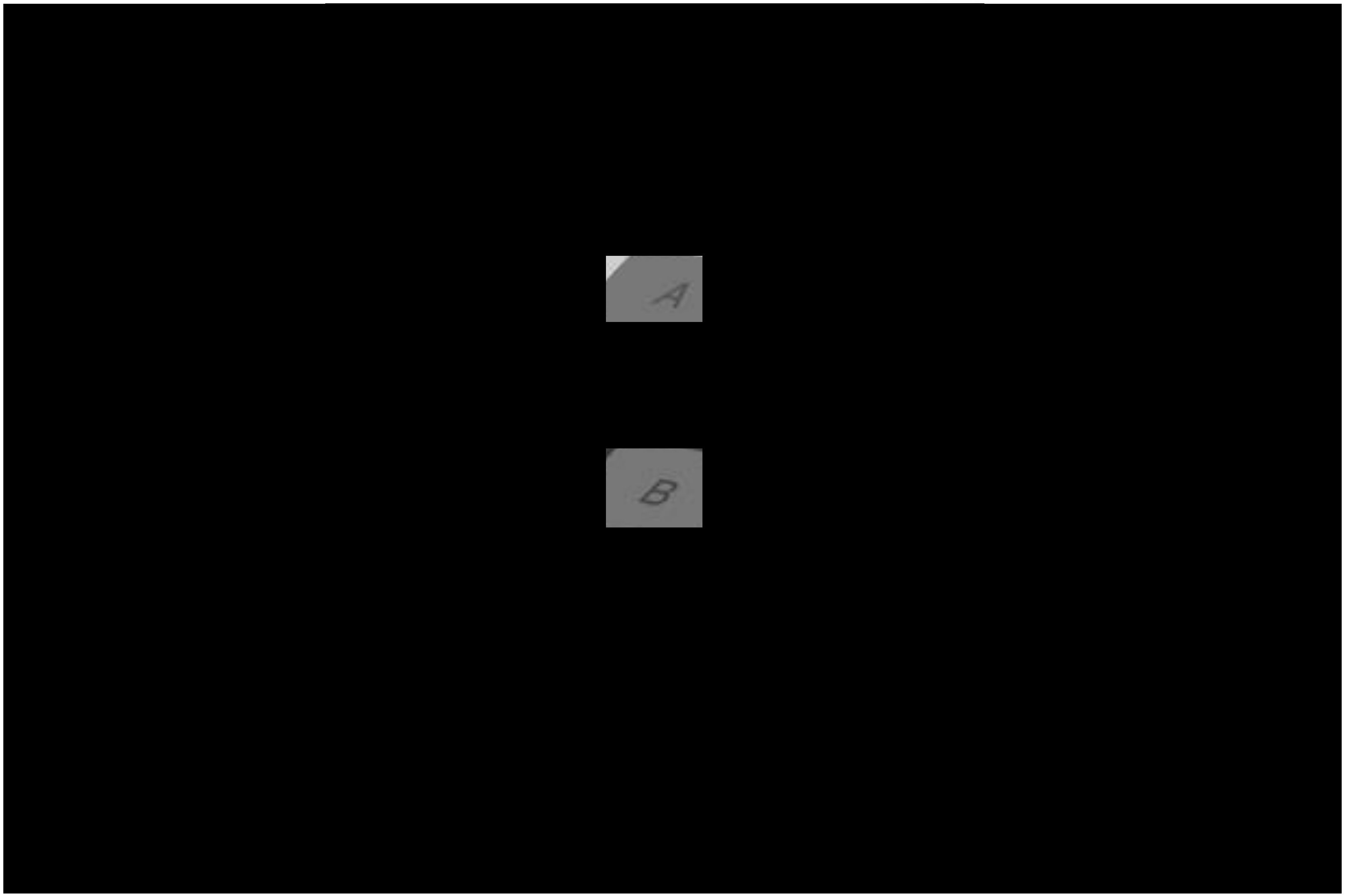
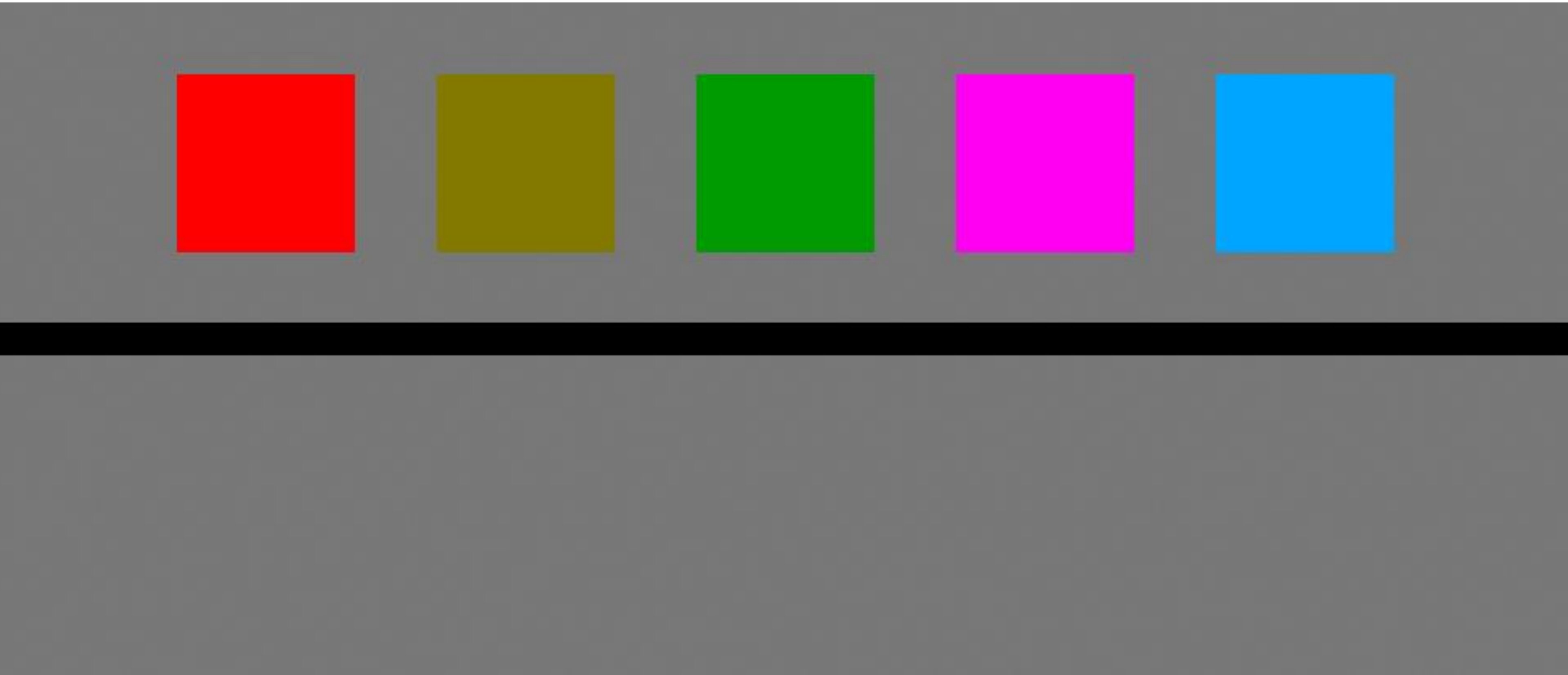


Helmholtz–Kohlrausch effect



Color Spaces

Many ways to encode color

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Very tenuous relationship between these color spaces and what we **actually** see

(100,50,50) looks different depending on:

- device
- surrounding color
- background lighting
- etc

Perceptually-Normalized Colors

Idea: represent colors based on how they will be perceived

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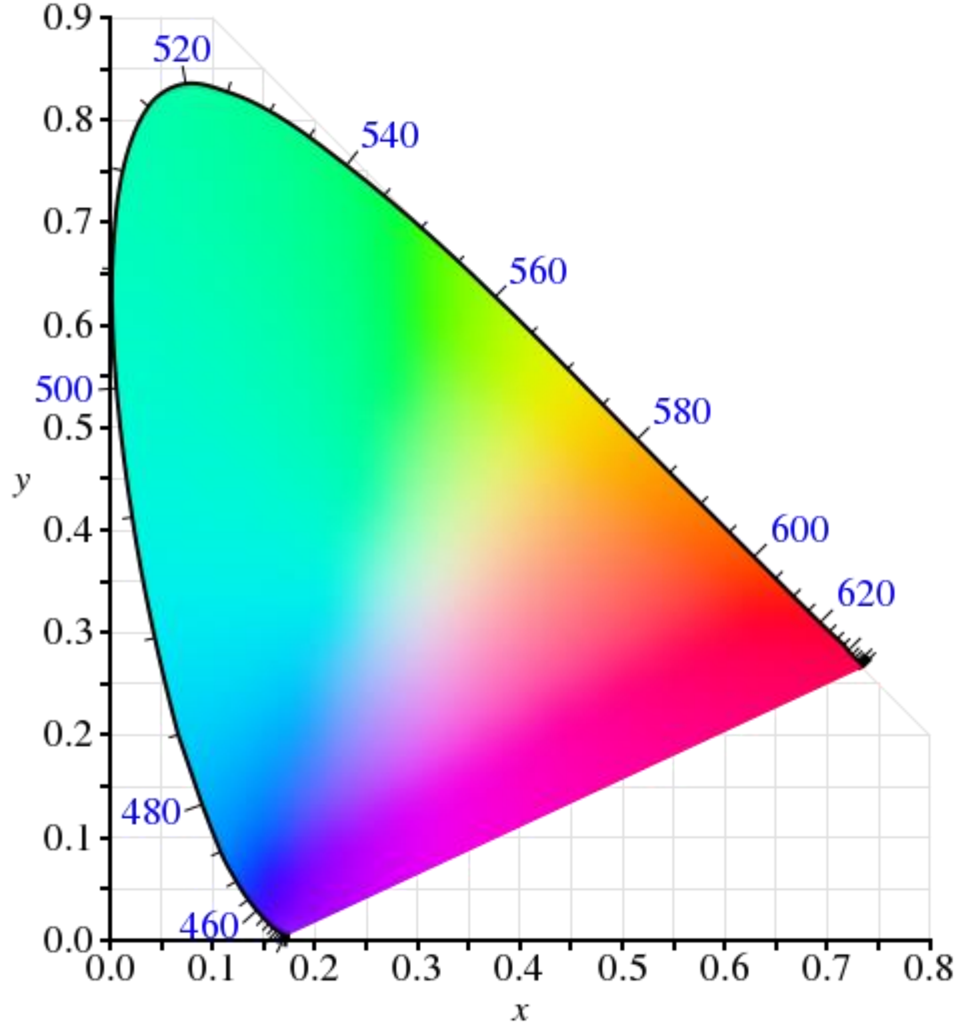
CIE 1931 XYZ color

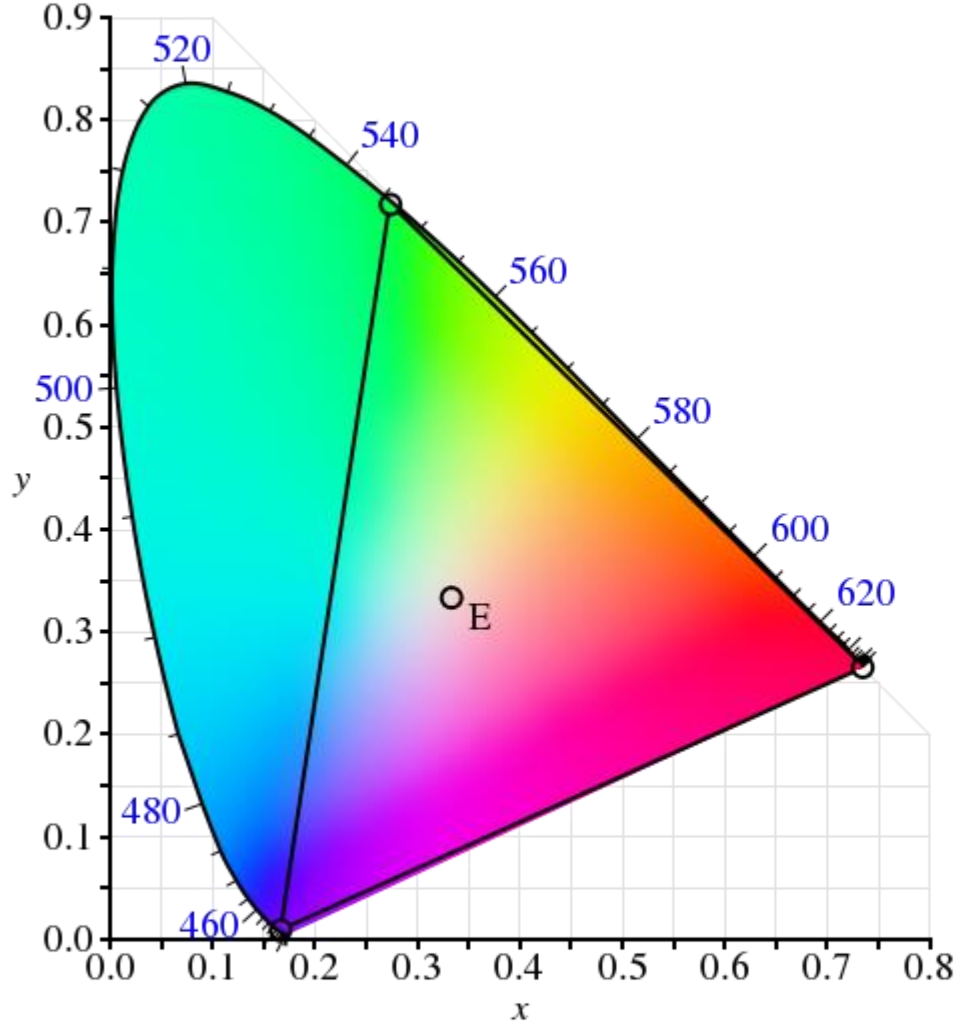
- based on extensive experiments
- maps out all possible colors perceivable by the human eye

CIE XYZ



0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0
y
520
540
560
580
600
620
500
480
460
0.0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
x

CIE XYZ



Devices can display some subregion of this space

Perceptually-Normalized Colors

Idea: represent colors based on how they will be perceived

CIE 1931 XYZ color

- based on extensive experiments
- maps out all possible colors perceivable by the human eye

Other such spaces exist (L*a*b*, etc)

How Fast Can The Eye See?

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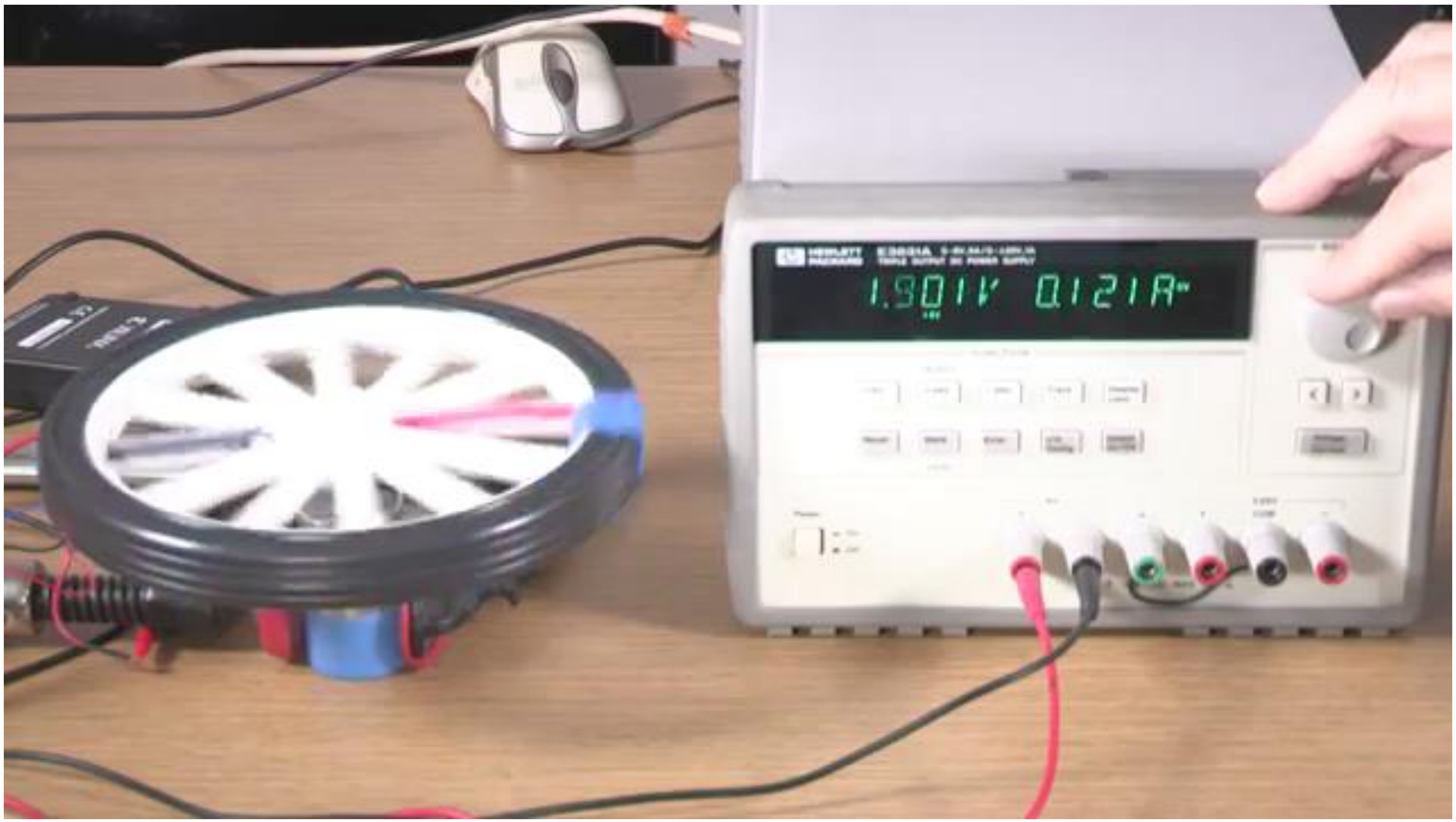
Our brains trained for continuity of motion

- a few FPS is enough if motion gradual
- motion blur

Wagon Wheel Effect



Wagon Wheel Effect

Temporal aliasing

Very noticeable on film

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Temporal aliasing

Very noticeable on film

- also in stroboscopic conditions
- CFLs
- humming