Light and Color

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Preview

The brain creates an image based on the signals it gets from the light entering our eyes:

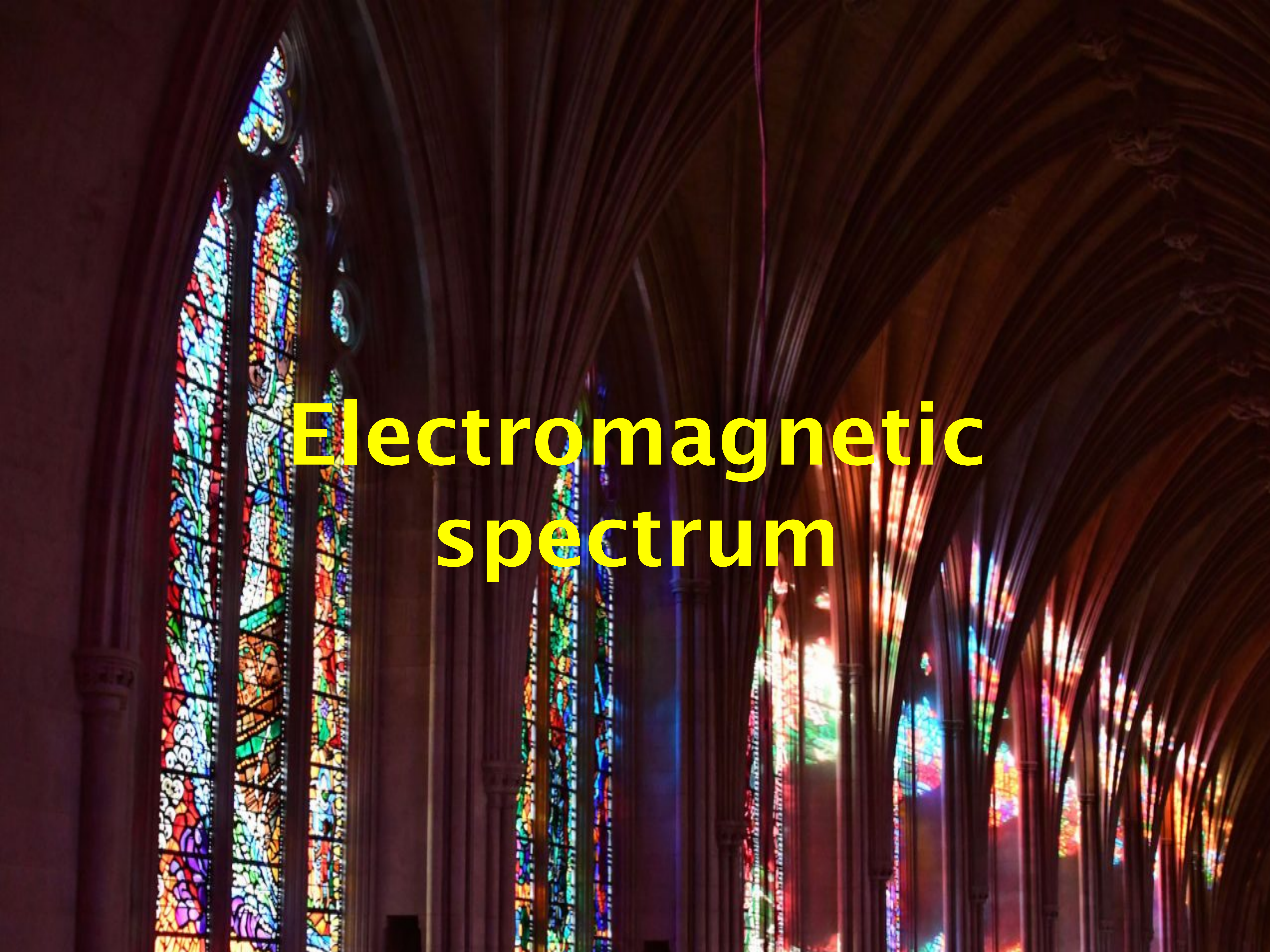
- **This light may come <u>directly</u> from a light source**
  - **e.g. sun, light bulbs, computer monitor, cell phone, etc.**

- **Or the light from a light source may <u>bounce off</u> of various materials, and be modified, before it hits our eyes**
  - **e.g. creating color, brightness, dullness/shininess, etc.**

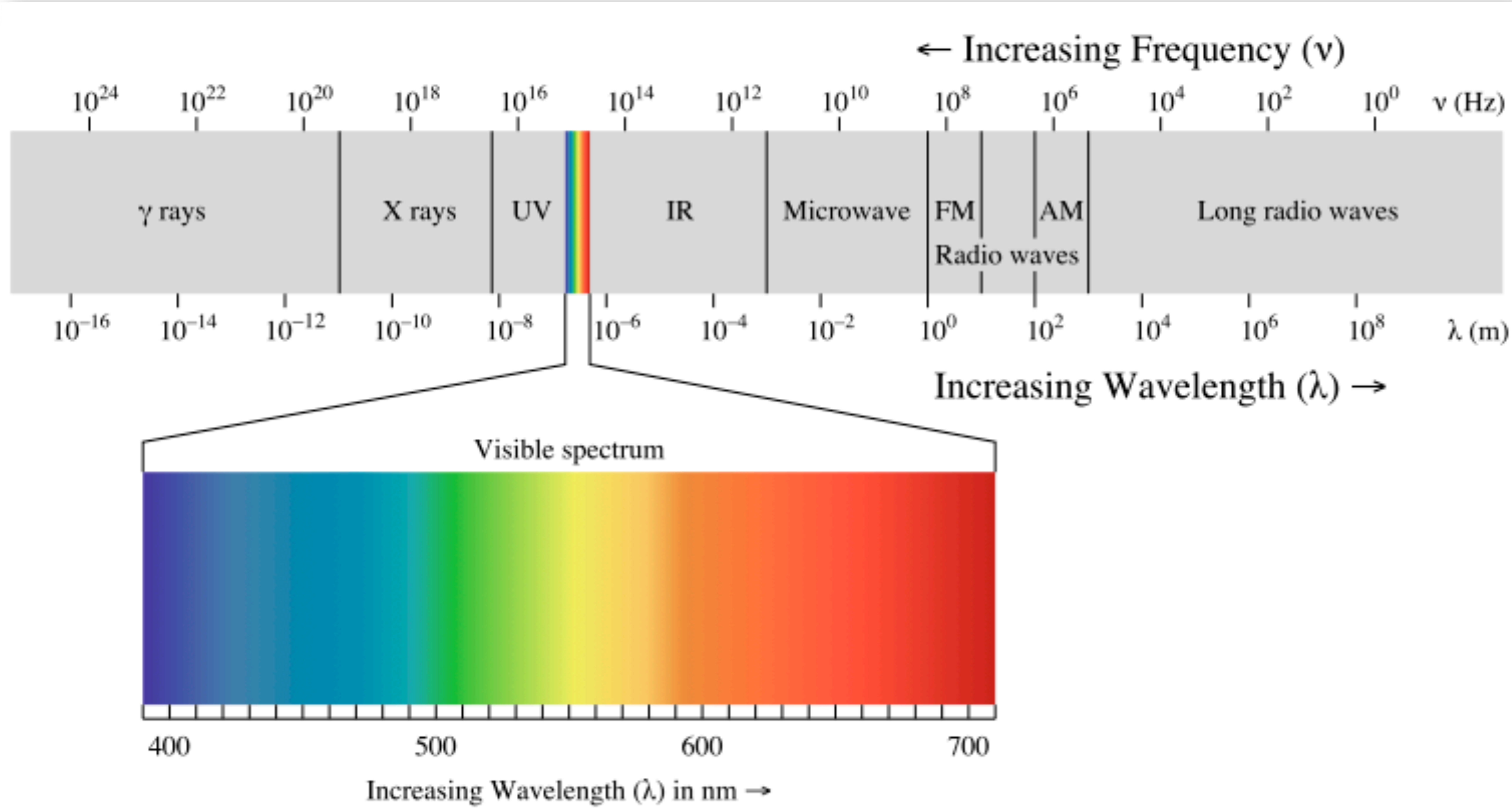
- **Or the light may <u>pass through</u> various materials before hitting our eyes**
  - **e.g. stained glass windows, water, etc.**

Understanding <u>the physics of light (optics)</u> and how we deal with this via both software and hardware is very important to computer graphics…

Electromagnetic spectrum



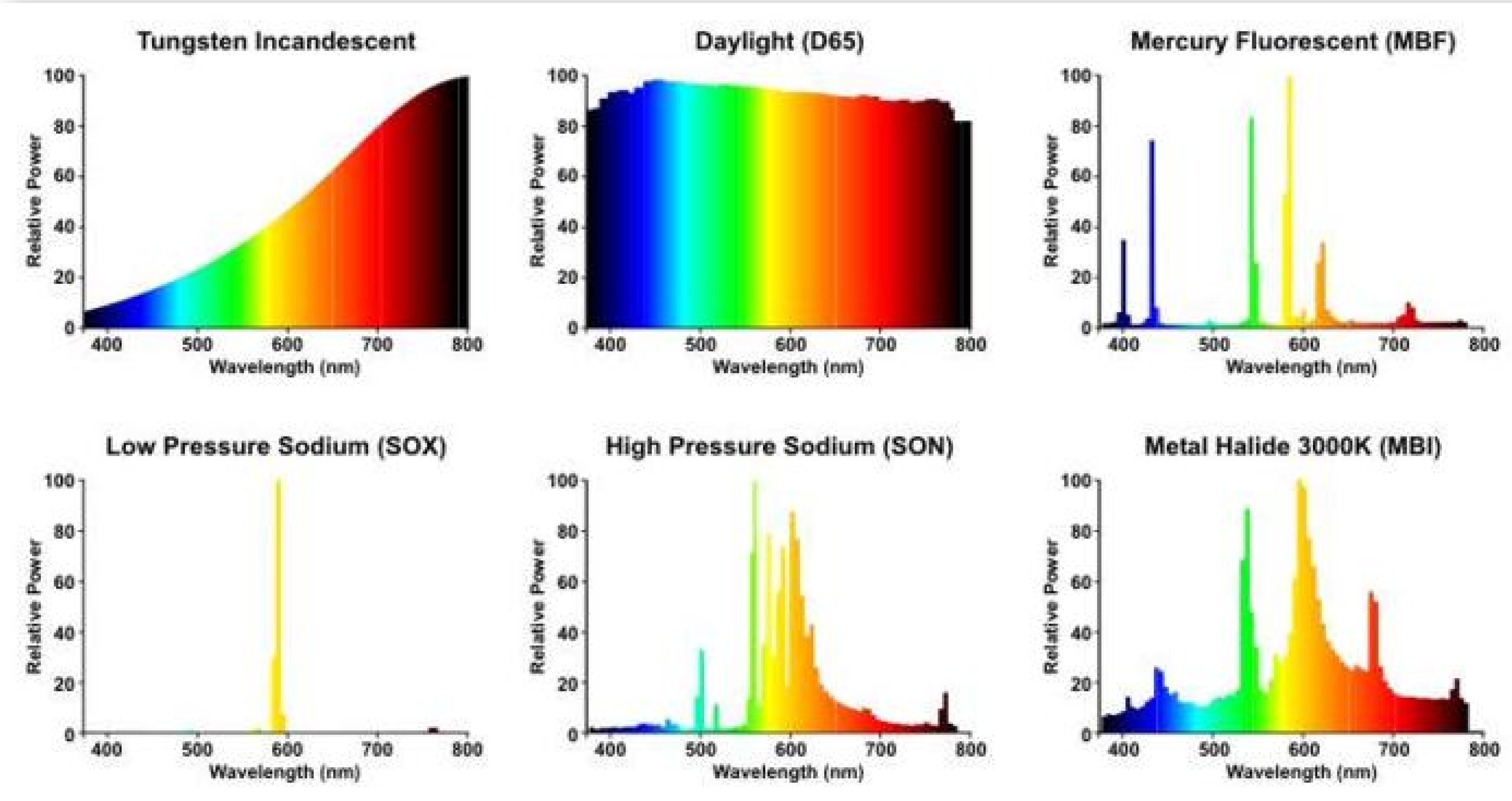
Electromagnetic Spectrum



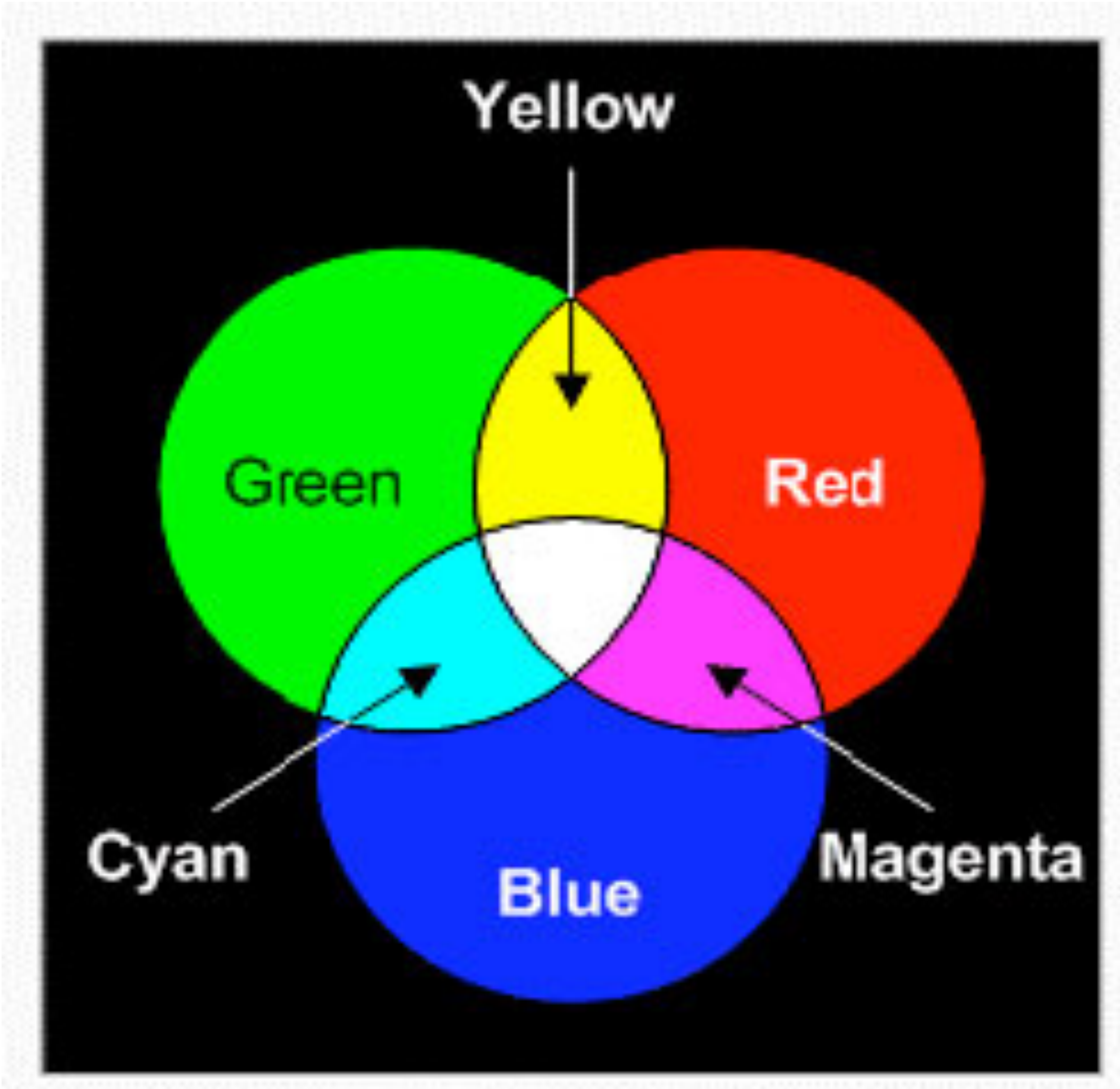
Visible light has wavelengths ranging from 400 nm to 700 nm

(wikipedia)

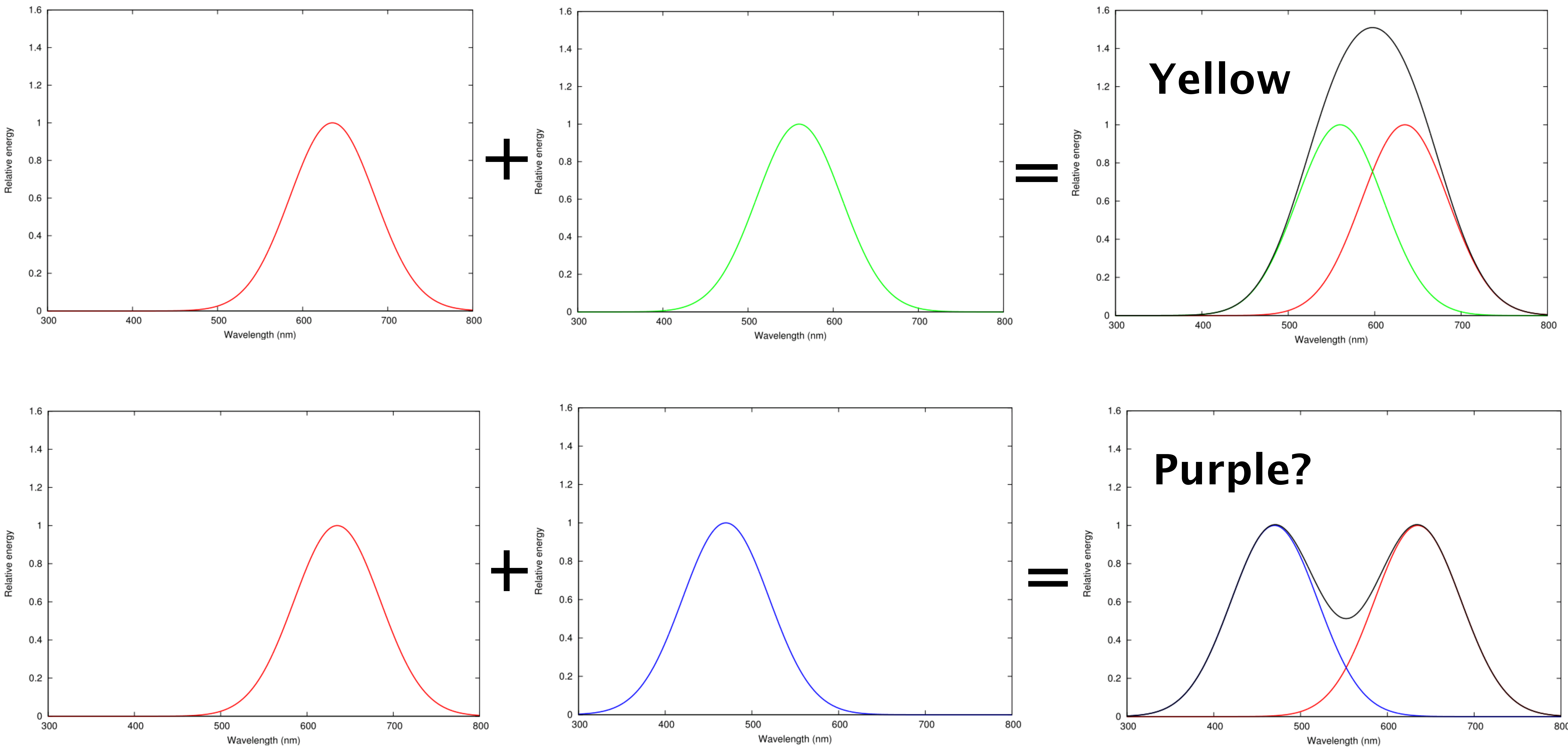
Relative Power Distribution of Lights



Adding Light Energy

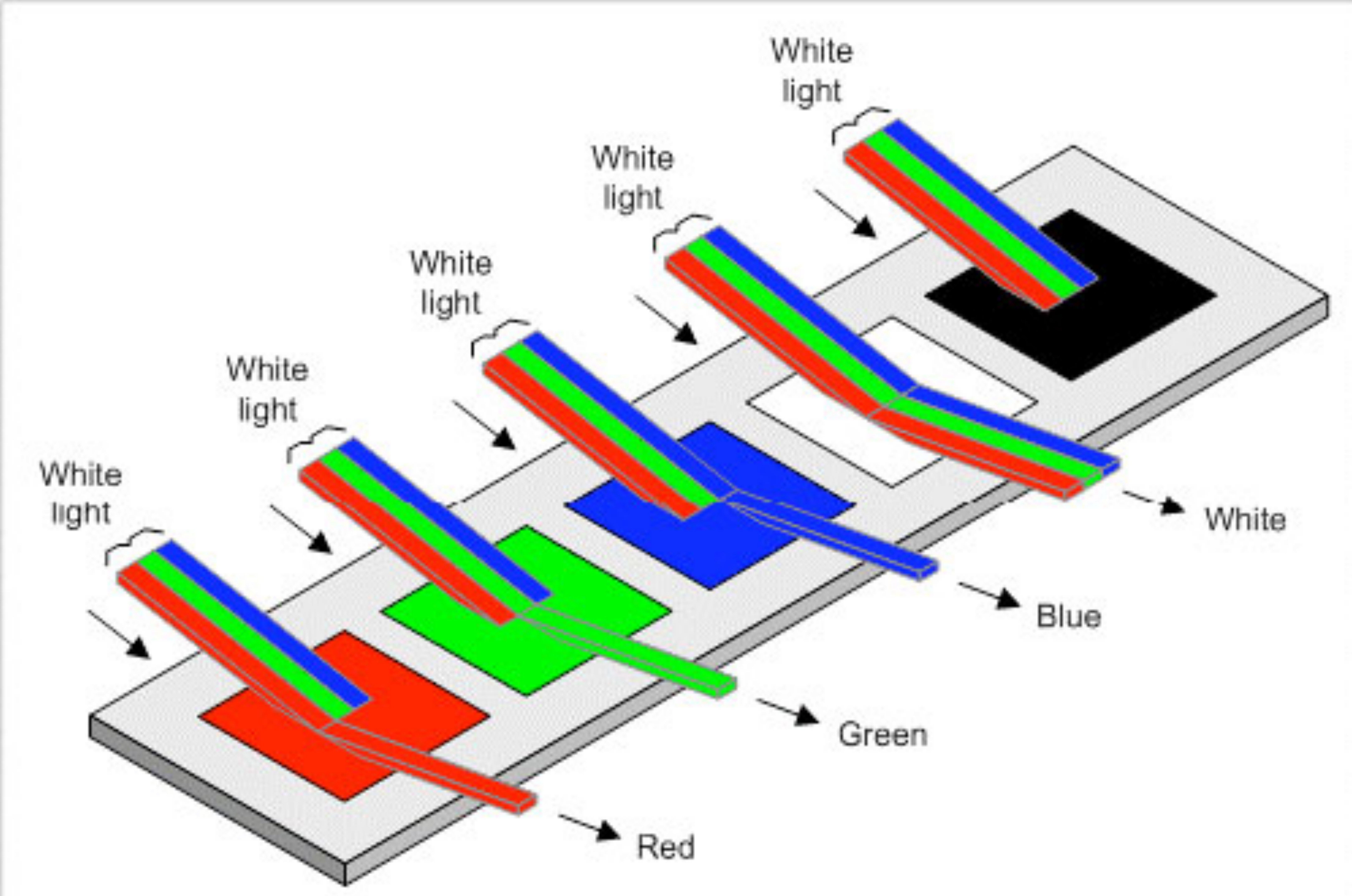


Adding Light Energy



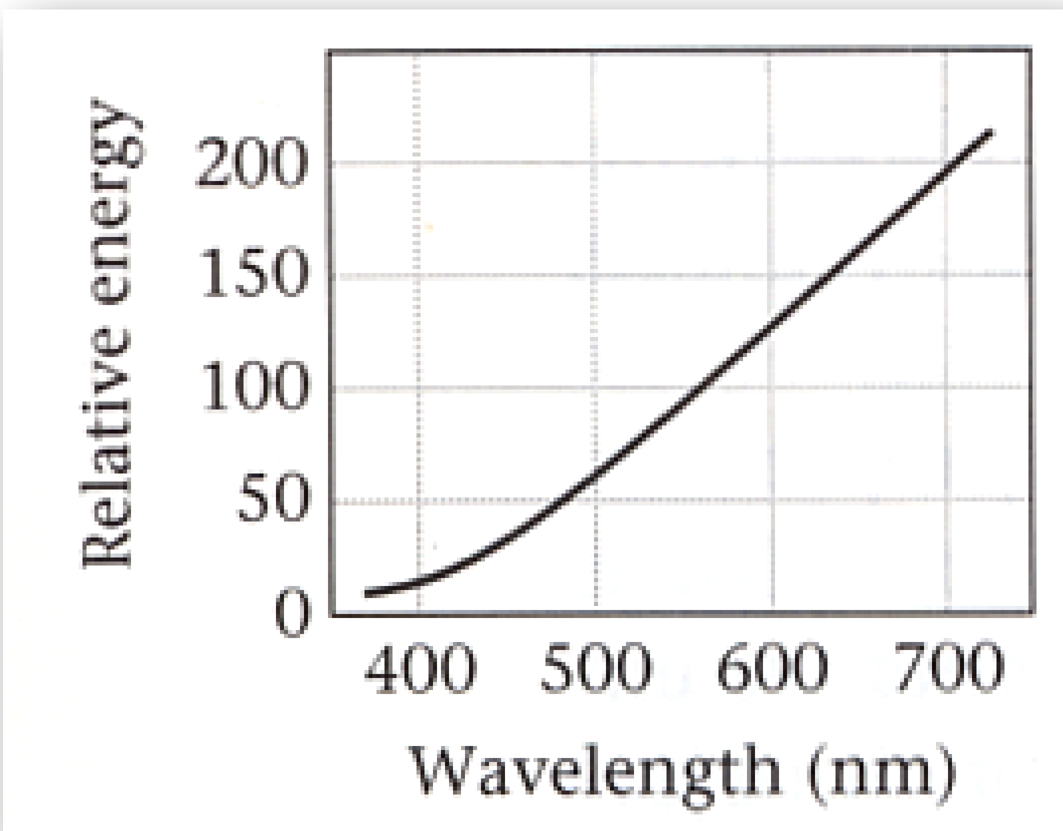
$$E(\lambda) = E_1(\lambda) + E_2(\lambda)$$

Reflecting & Absorbing Light



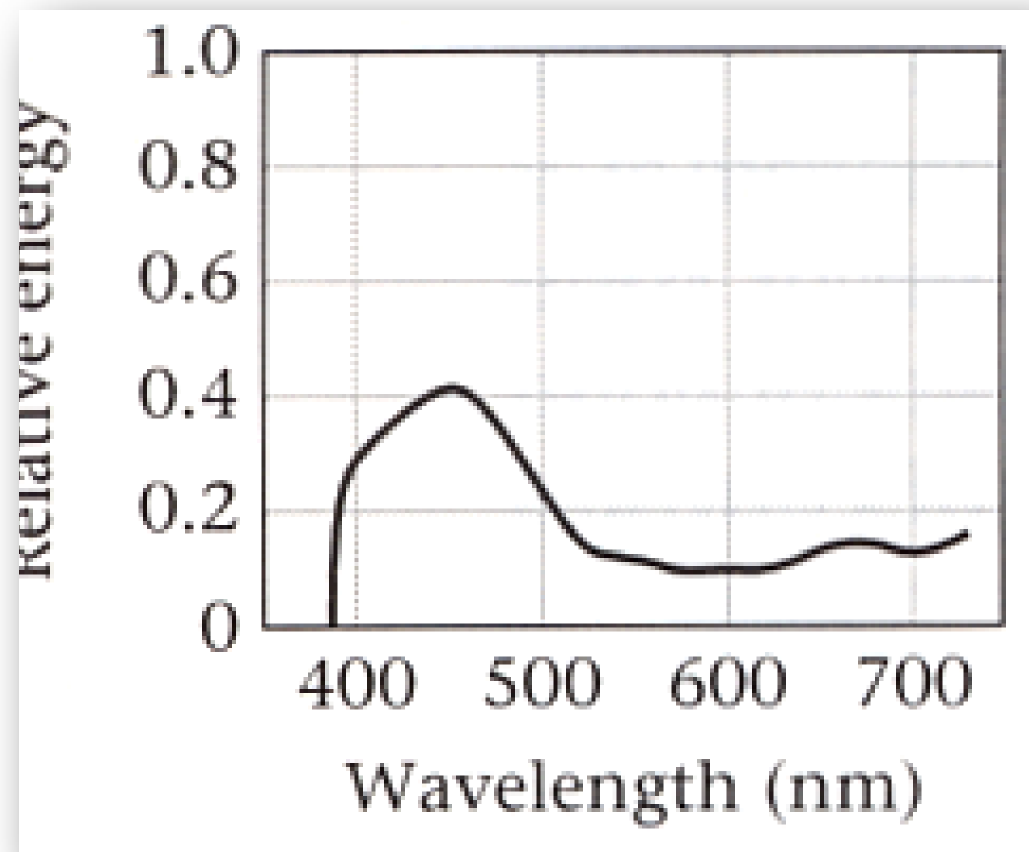
Shining white light on different colored paints

Reflecting & Absorbing Light



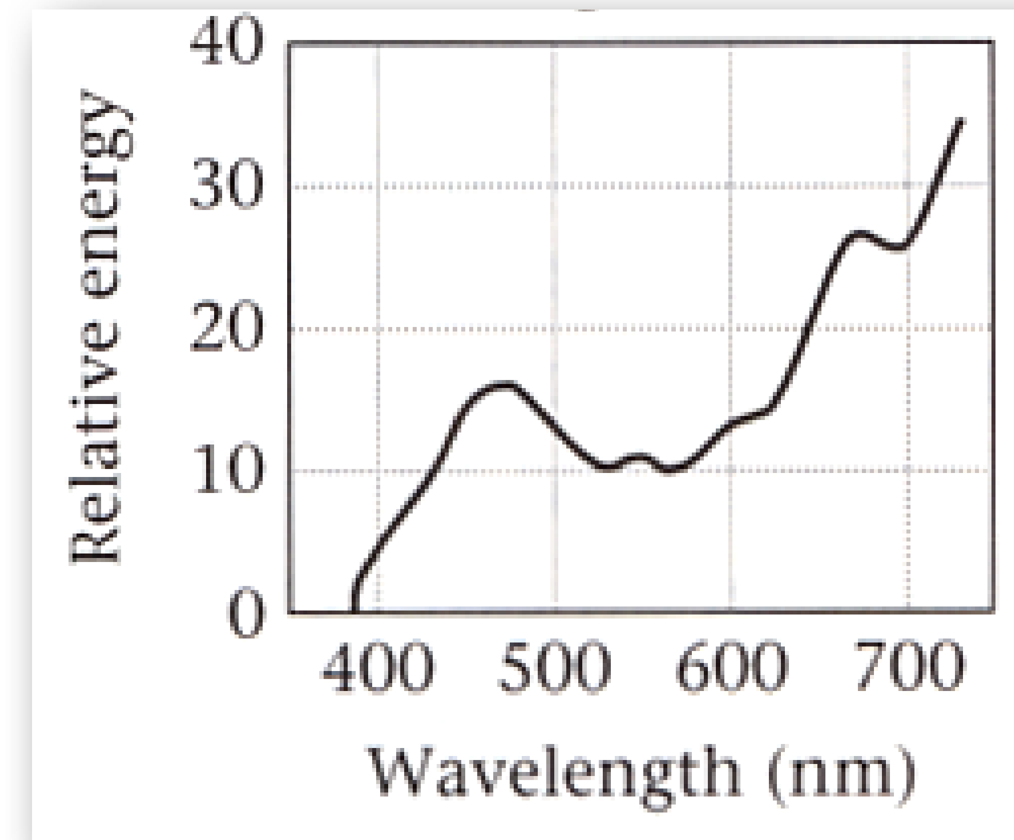
Light

×



Reflectance

=

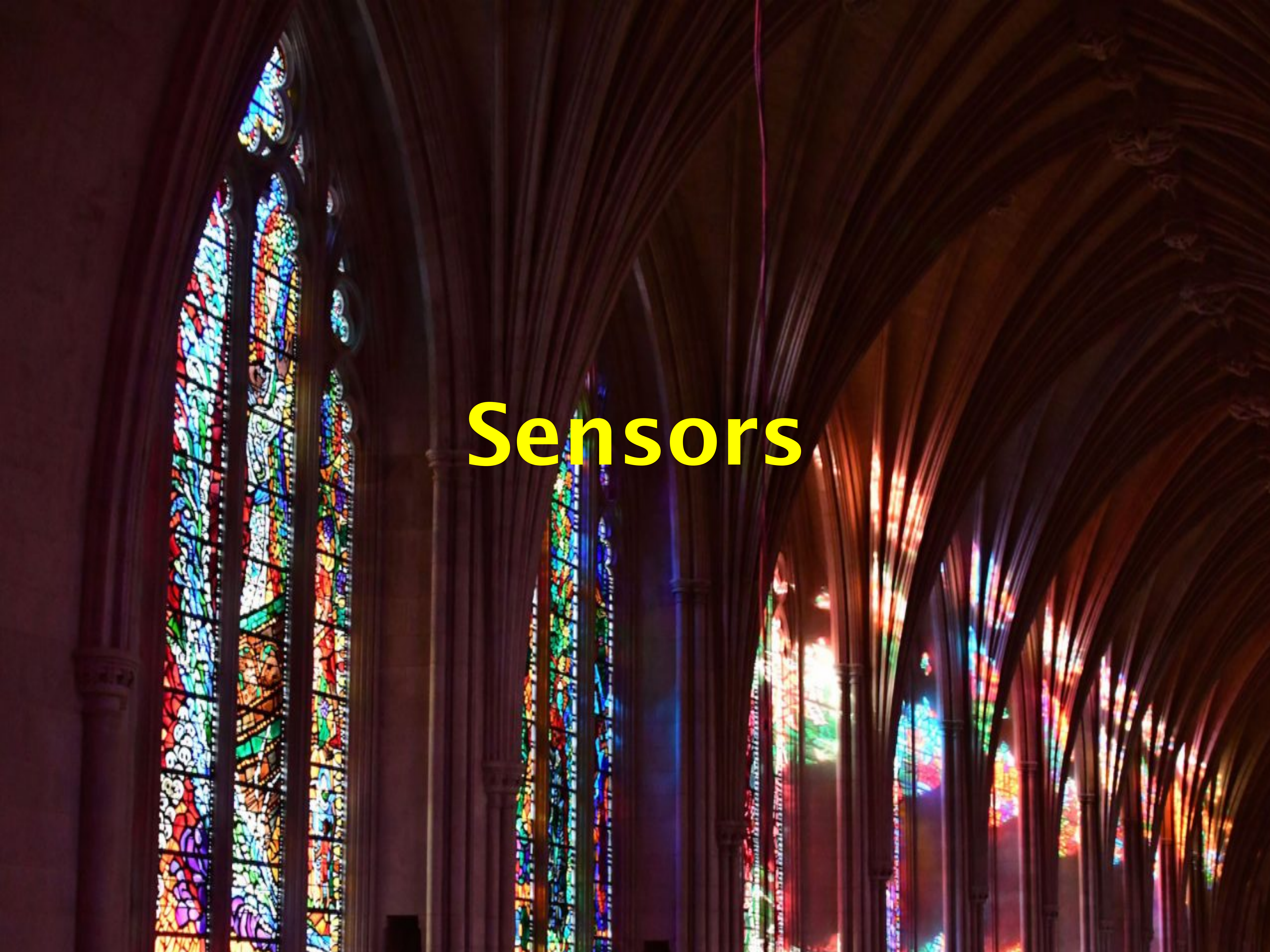


Reflected Light

$$R(\lambda) = r(\lambda)\, E(\lambda) = (1 - a(\lambda))\, E(\lambda)$$

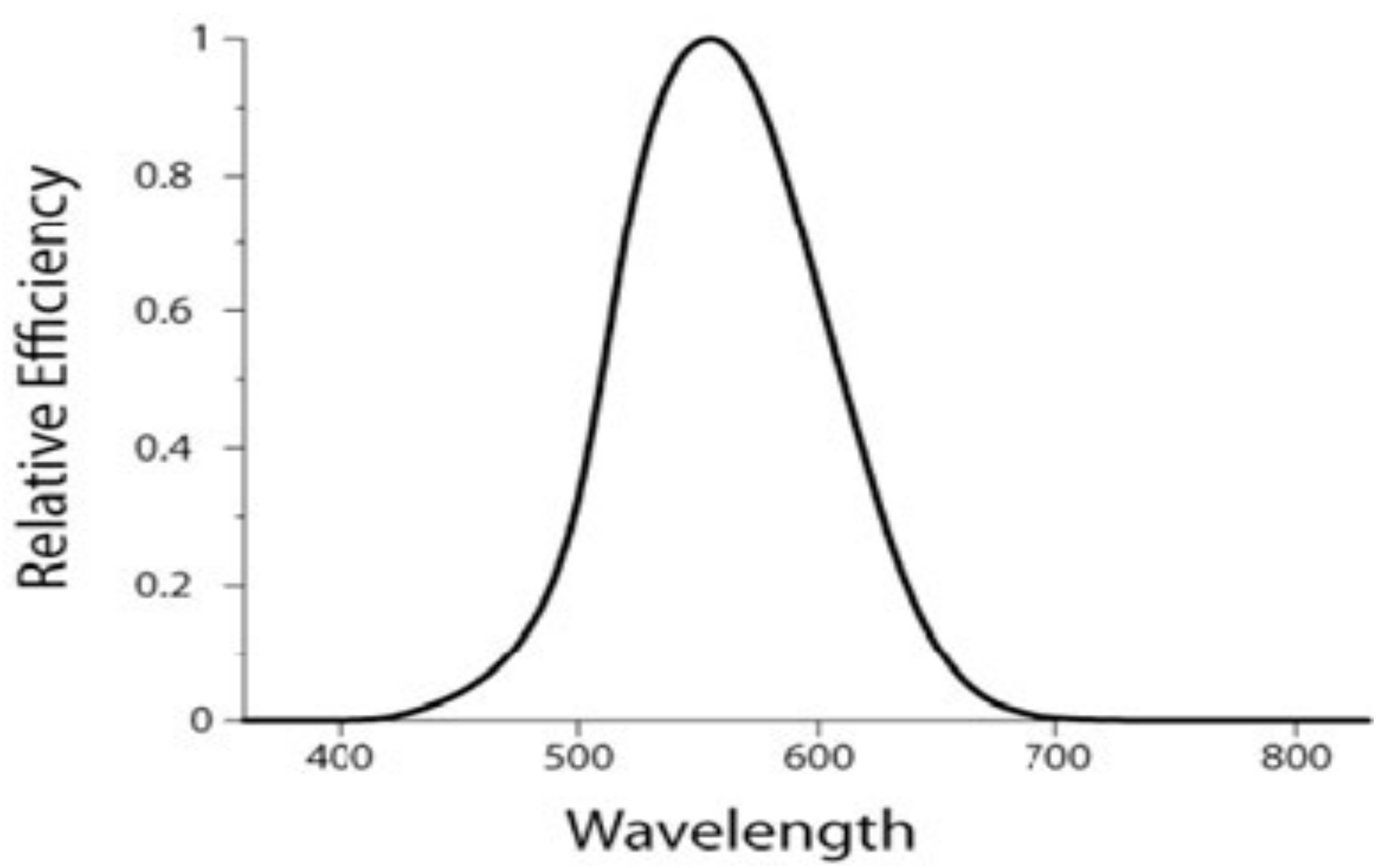
$$a(\lambda) + r(\lambda) = 1, \qquad 0 \leq a(\lambda), r(\lambda) \leq 1$$

Sensors



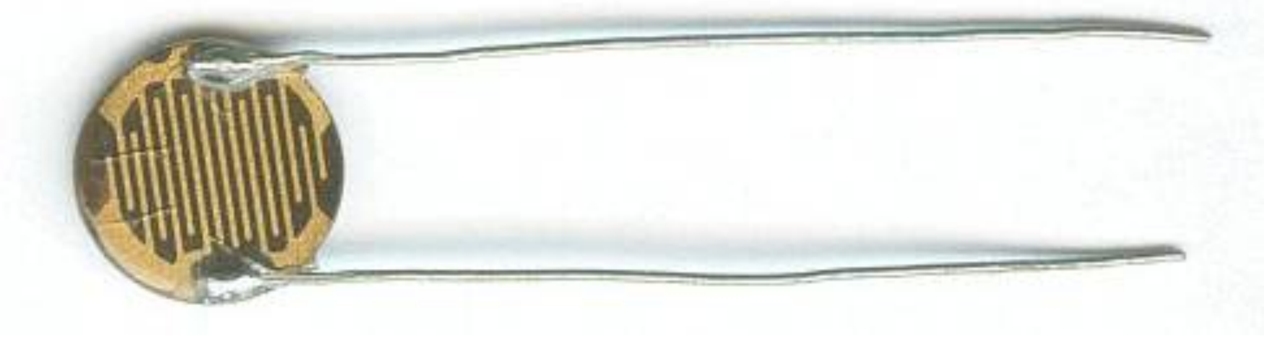
Absorption by Sensors

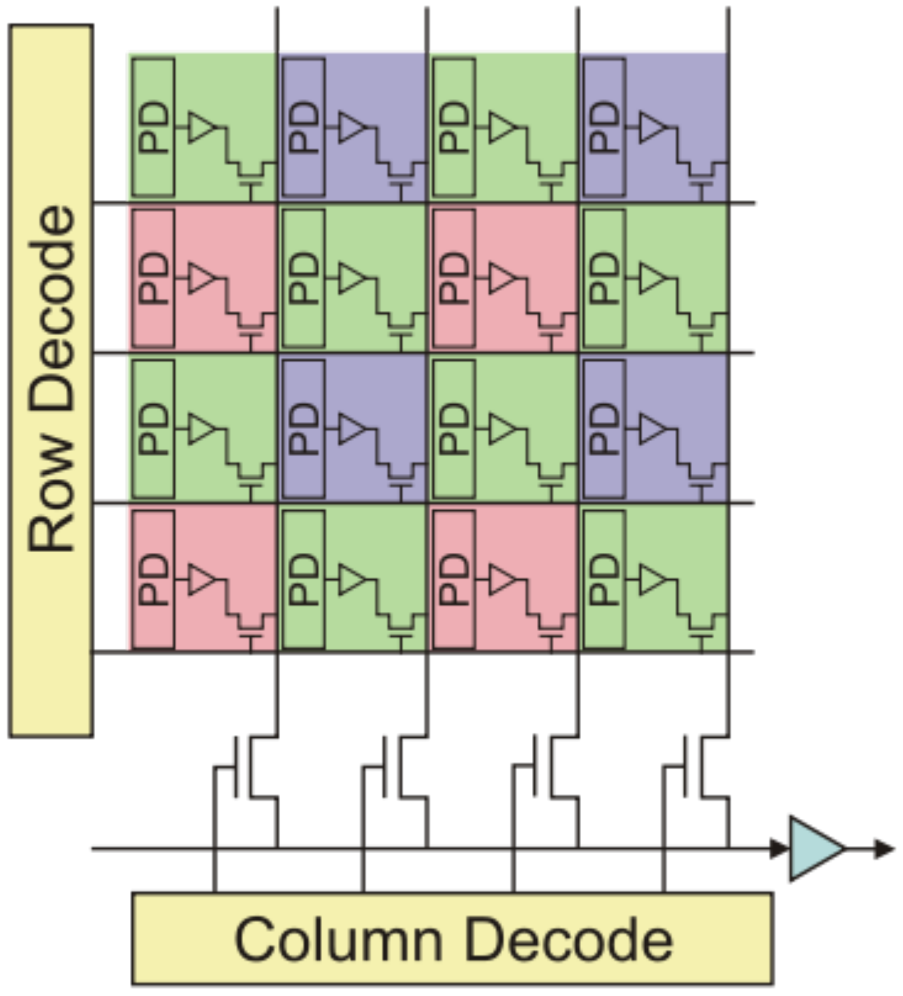
- **Sensors, cones, rods, etc.**
- **Response function (for absorption):**

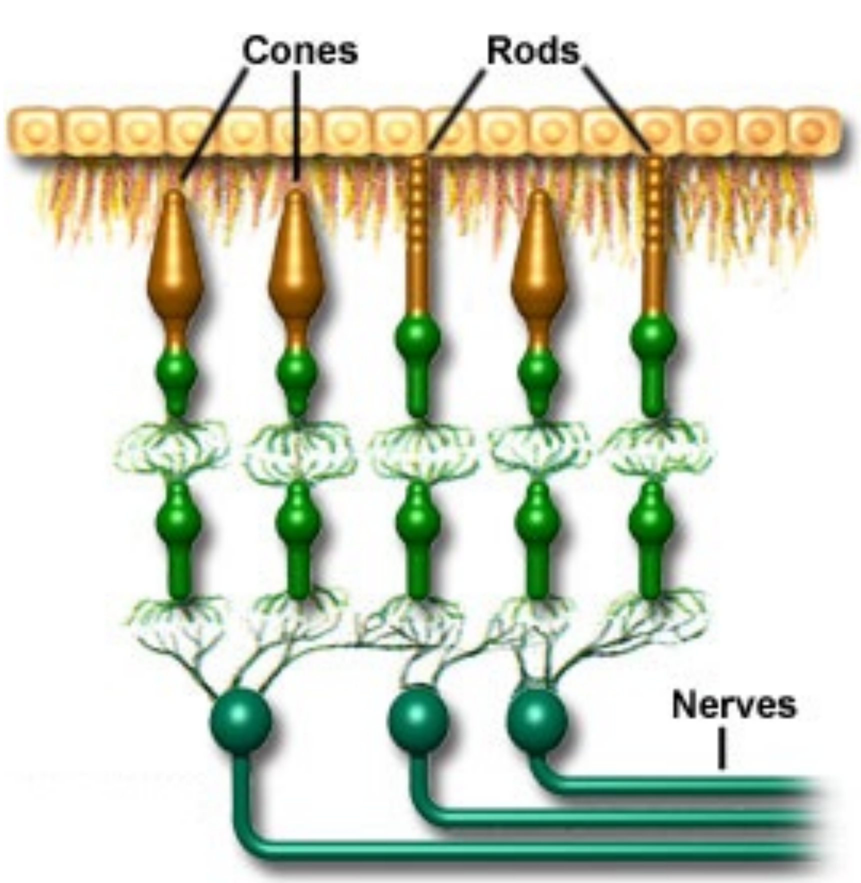


- **Signal power (energy per second):**

$$A = \int A(\lambda)\, E(\lambda)\, d\lambda$$

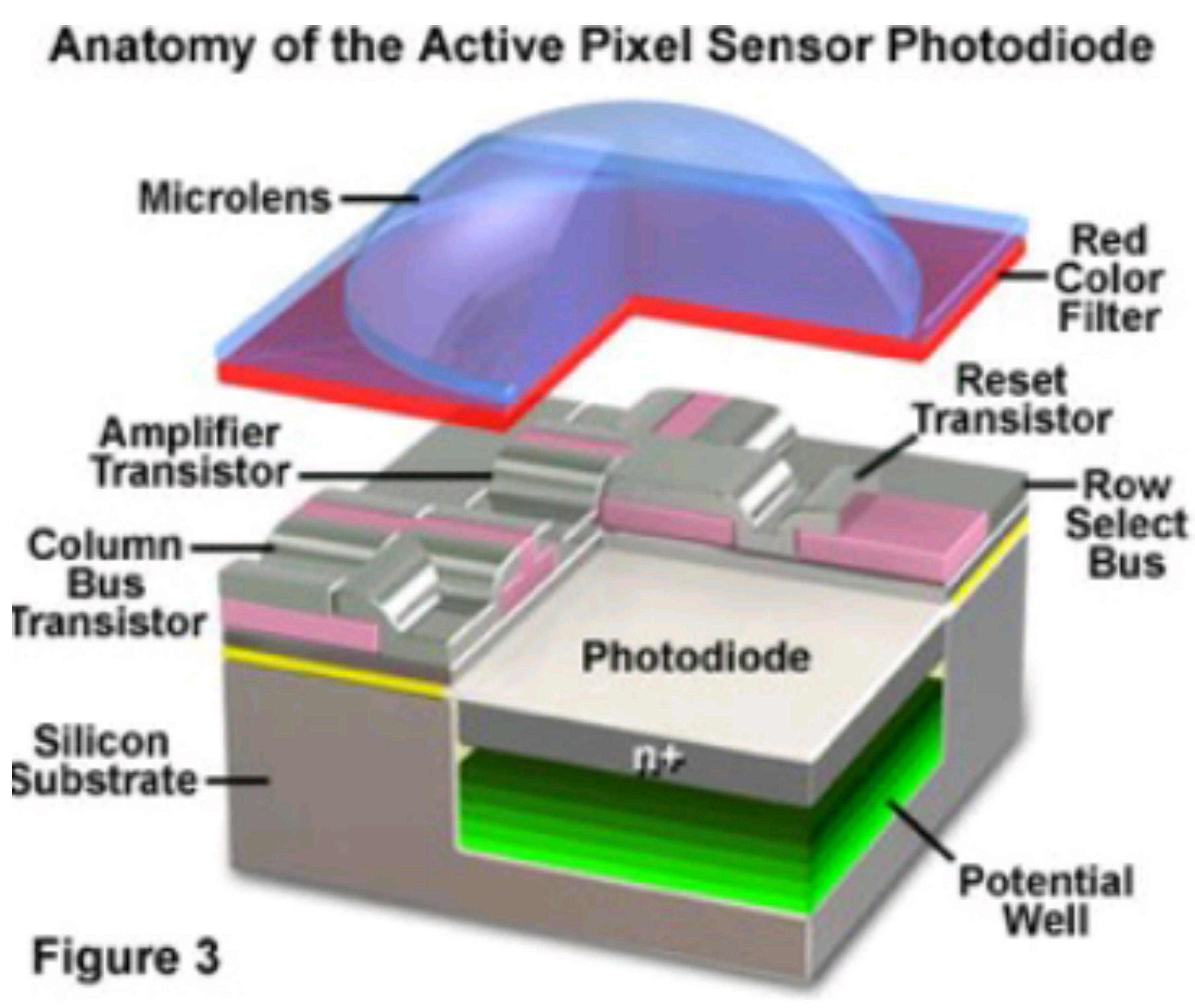




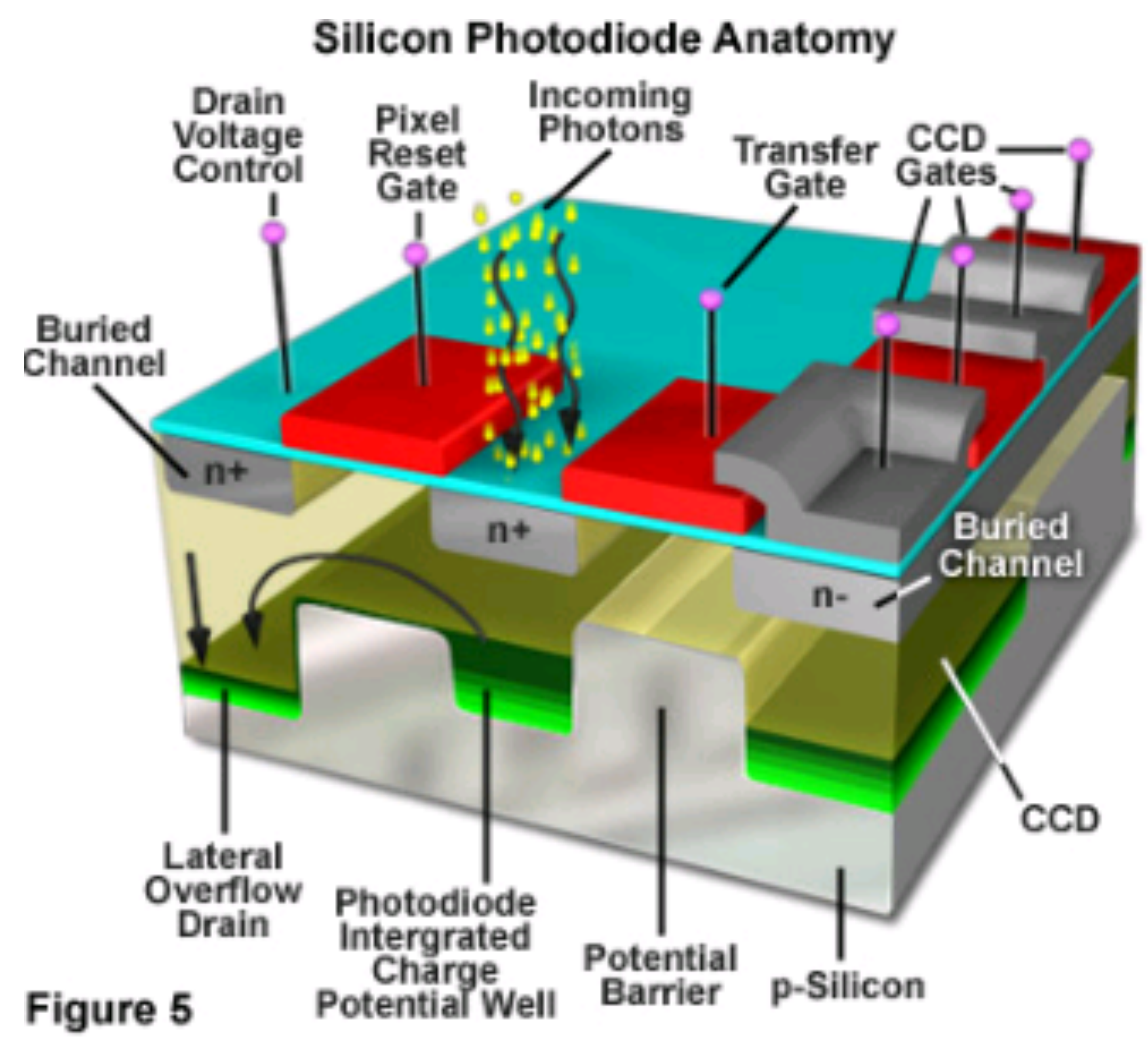


Electronic Sensors

- **Photoelectric Effect – materials generate electrons when hit by a photon**
- **Quantum Efficiency – not all photons will produce an electron**



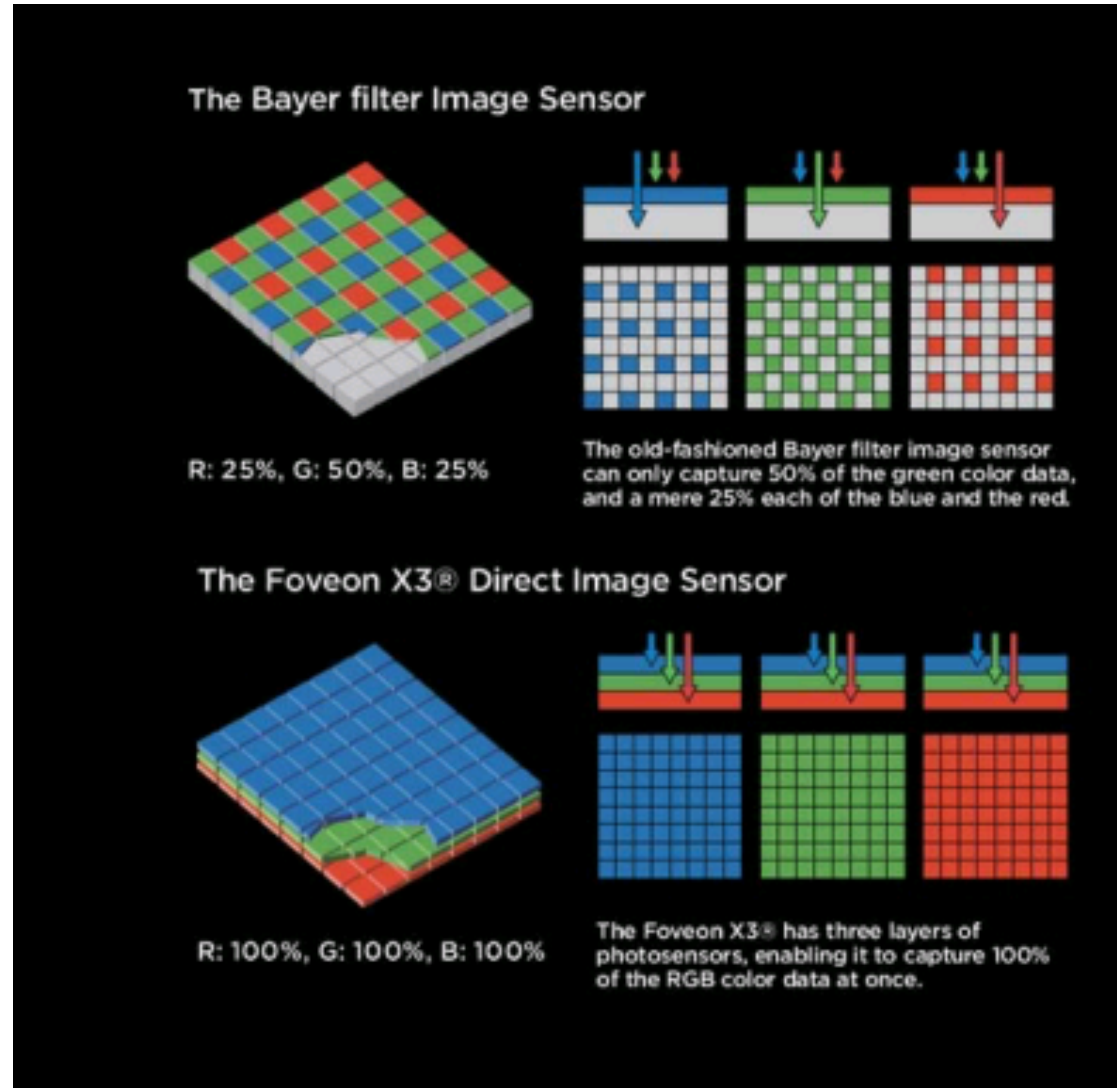
Complimentary Metal-Oxide Semiconductor (CMOS)



Charge-Coupled Device (CCD)

Camera Sensors (Red, Green, Blue)

- **Each sensor records incoming light energy per second (power)**
- **Each sensor captures only one signal (per unit time) for its entire 2D spatial area**
- **Color filters are used to limit the incoming light to a particular color (so we can use the same sensor for every color)**
- **<u>This does NOT measure the actual light spectrum!</u>**



camera mosaic

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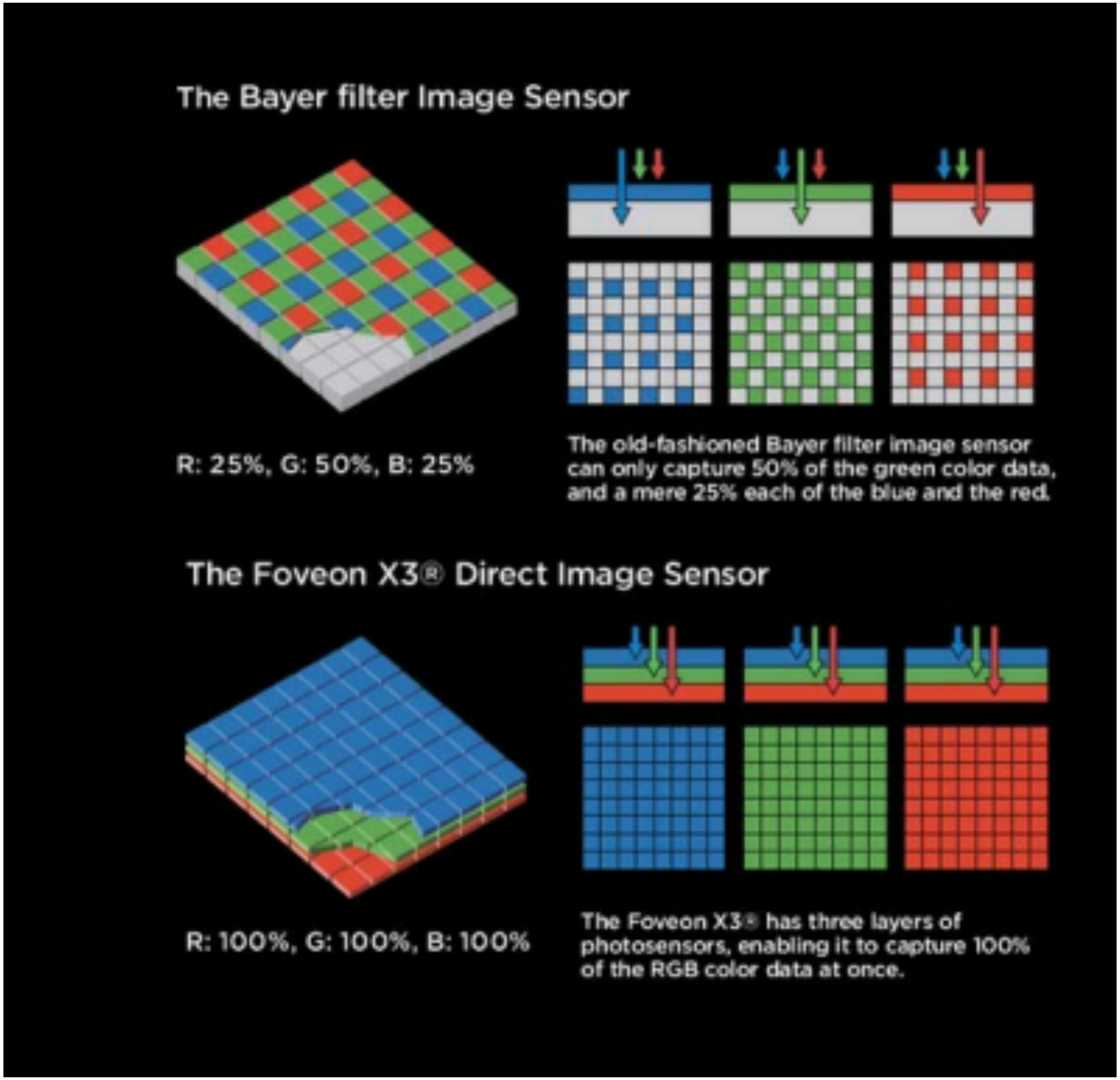
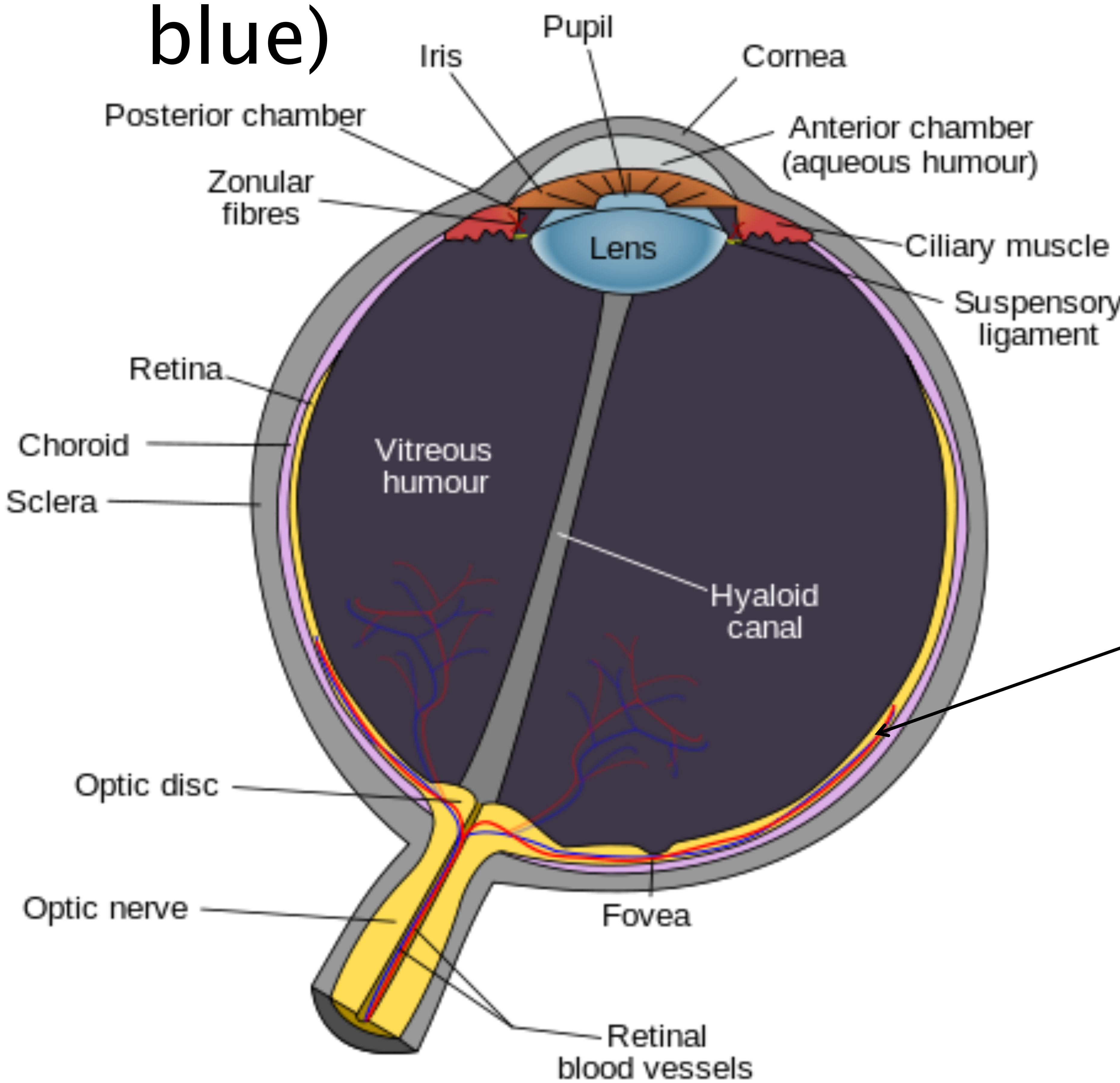
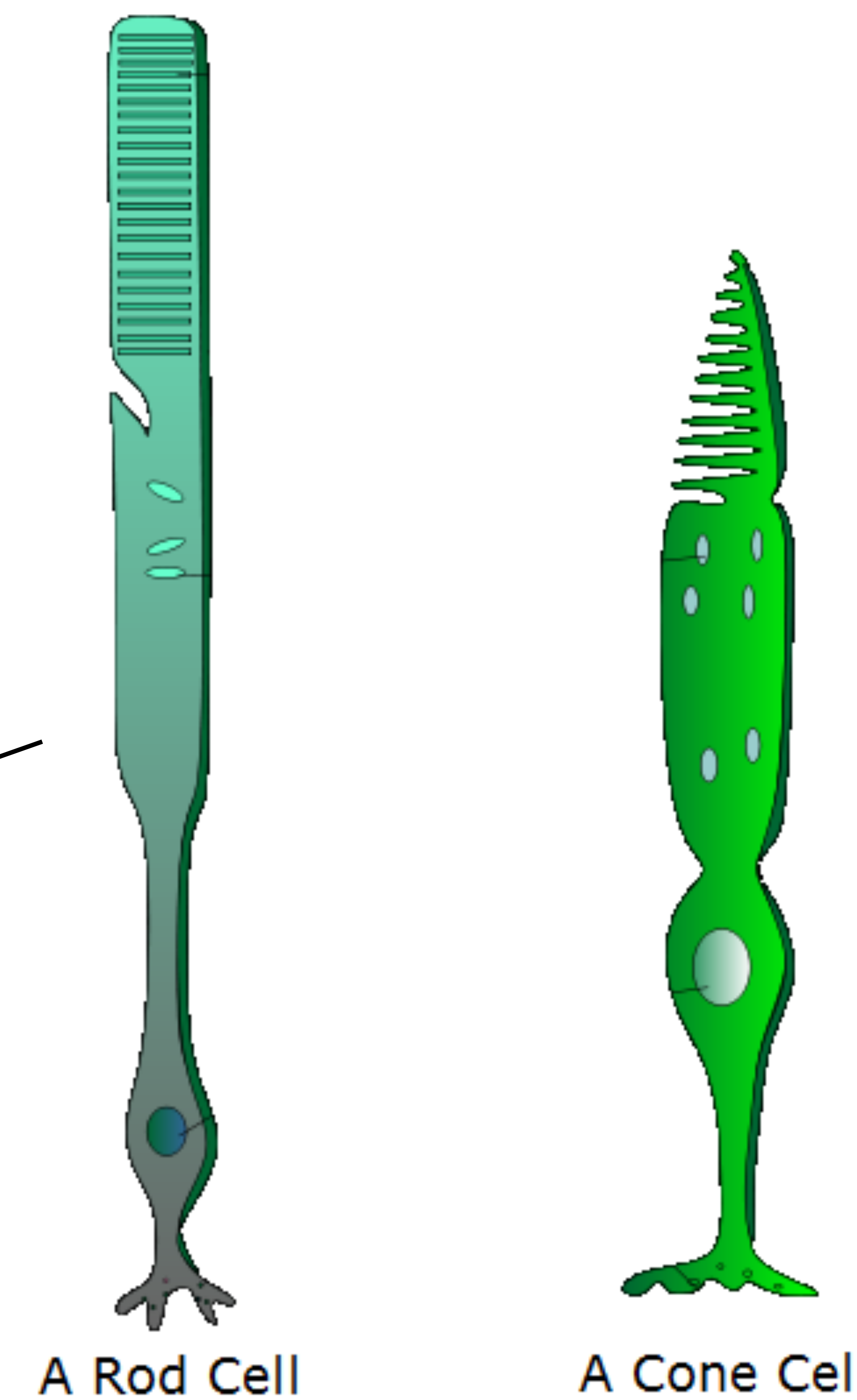


Human Eye

The retina has two kinds of sensors

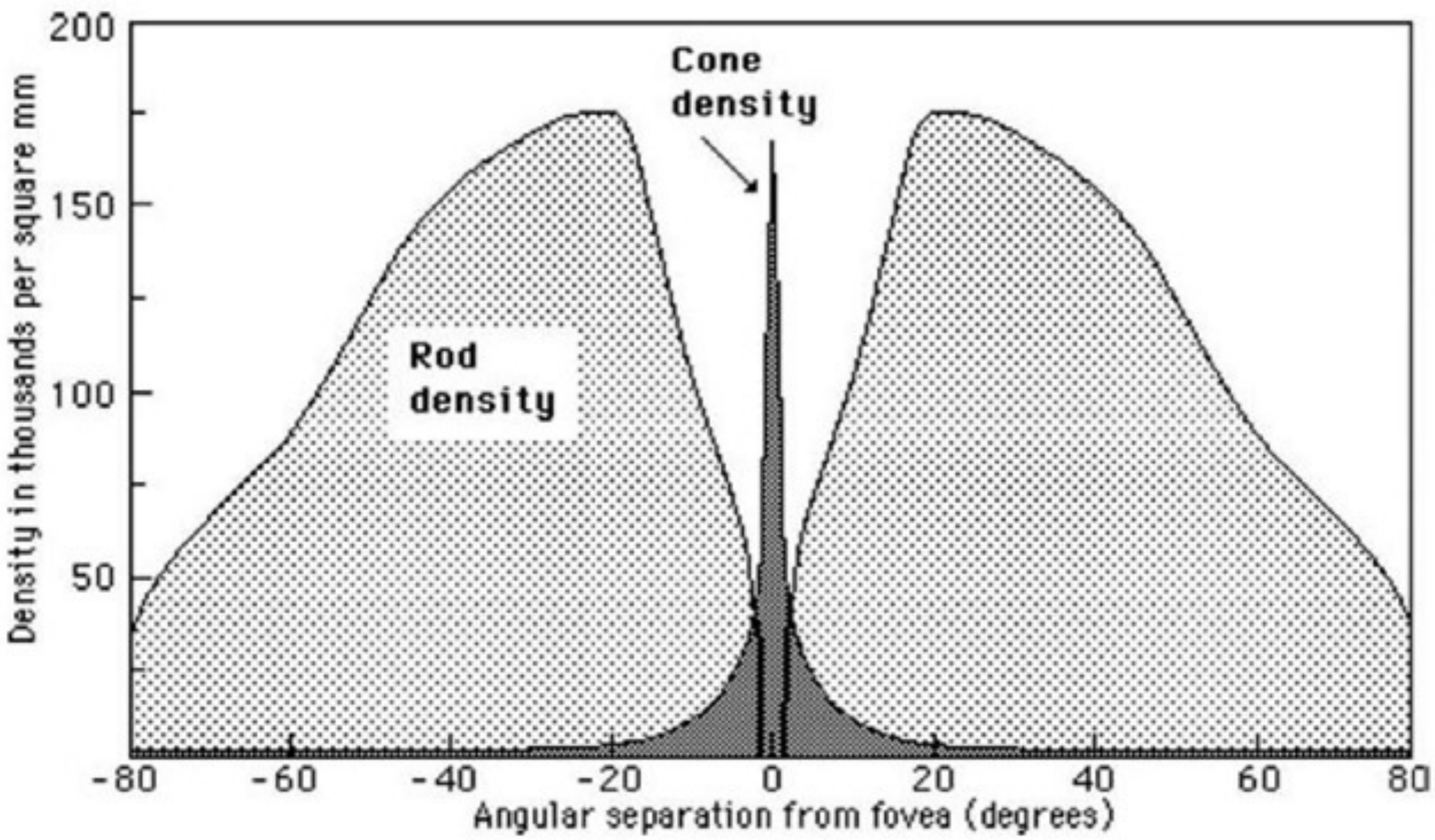
- Rods only measure light intensity
- 3 different cones measure three colors (red, green, blue)





Cones and Rods

- In <u>daylight</u> the signals from the rods are over-saturated, and humans see primarily with the <u>cones</u>
- The cones are densest at the center of the retina (the fovea), giving maximum detail for whatever the eye is looking directly at
- At <u>night</u> the cones are under-saturated, and humans see mostly with the <u>rods</u>
- The rods have virtually zero density at the fovea, which is why astronomers look out of the “side” of their eye



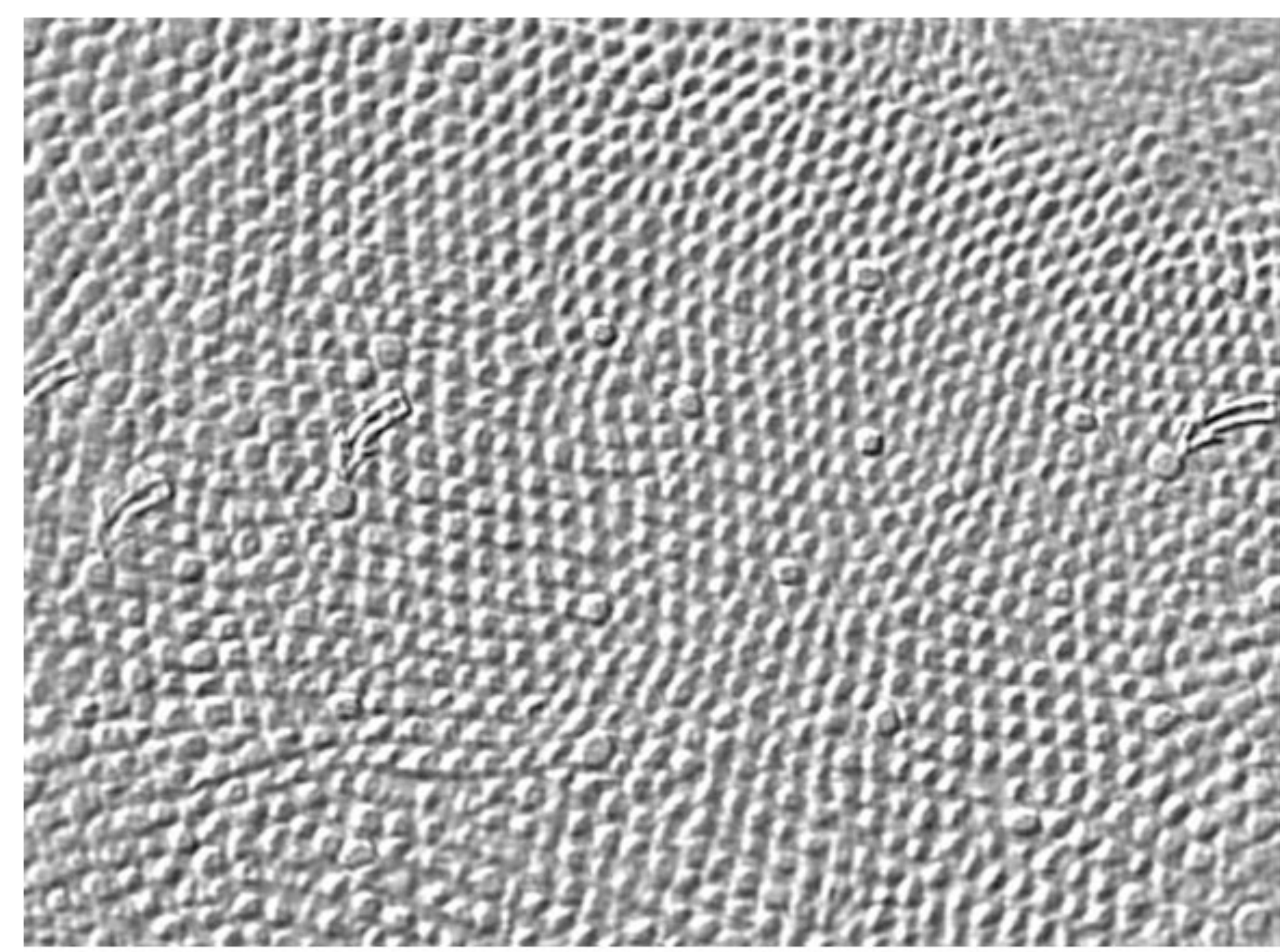
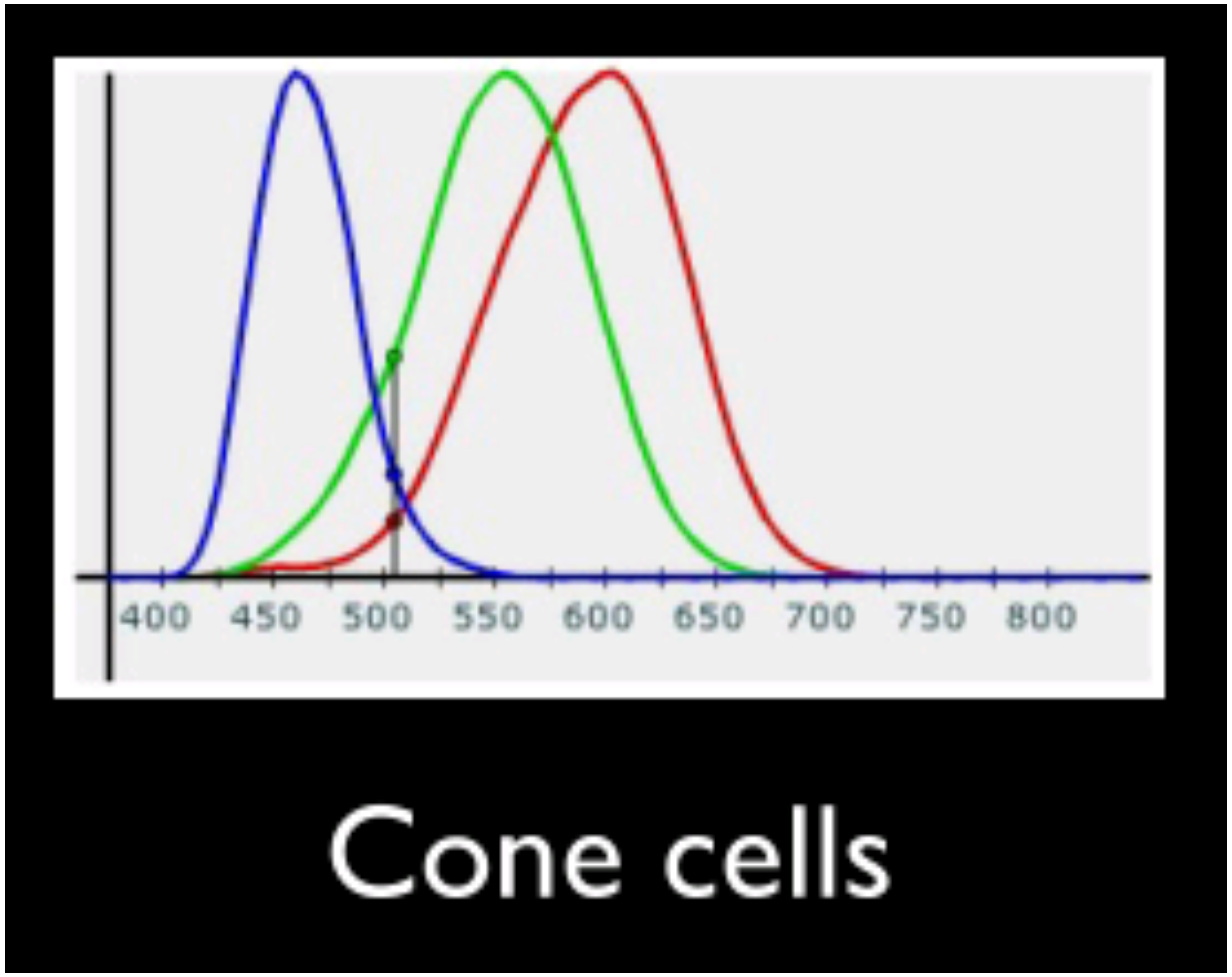
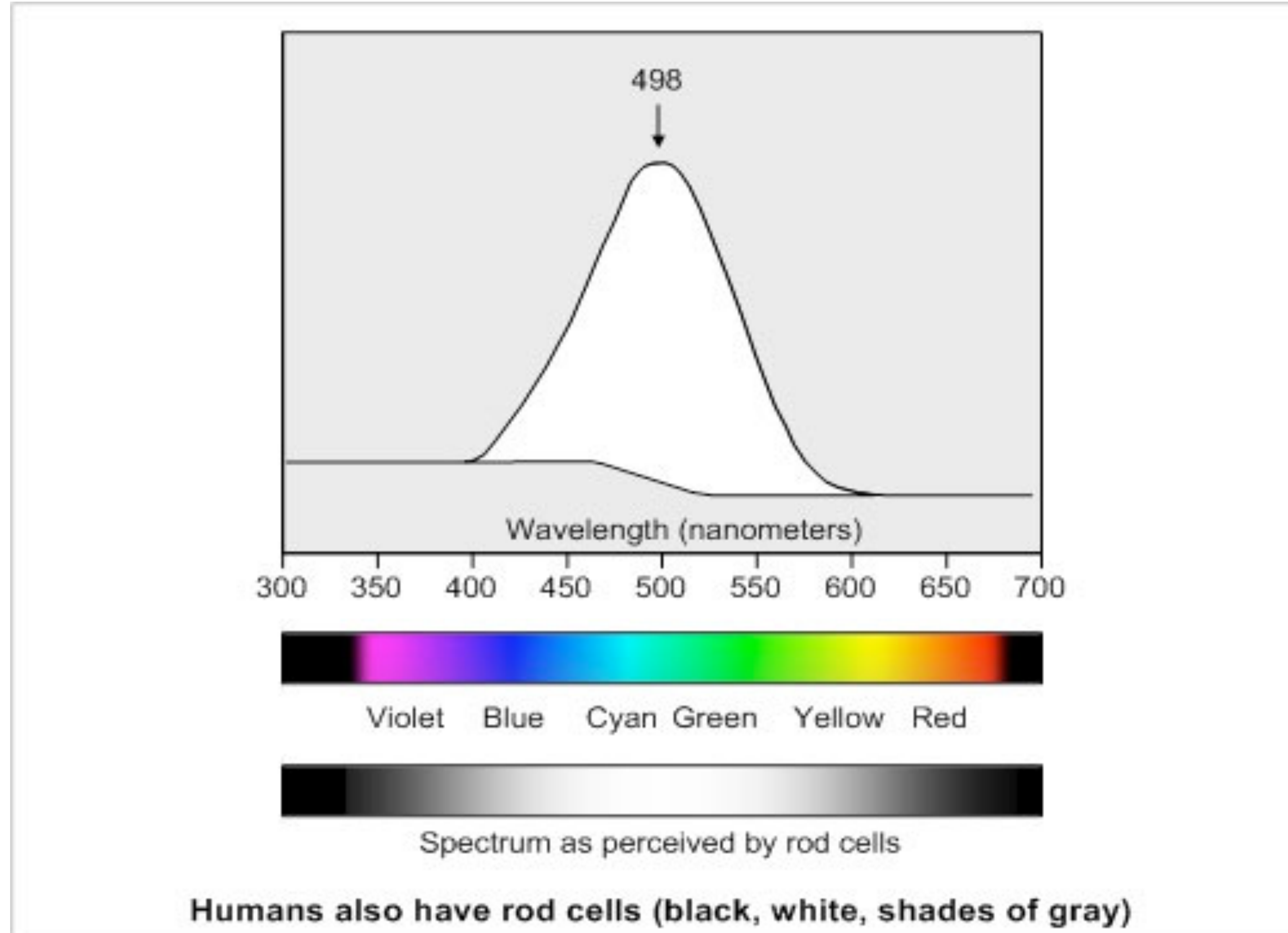


Fig. 13. Tangential section through the human fovea. Larger cones (arrows) are blue cones.

(Image from http://what-when-how.com/energy-engineering/lighting-design-and-retrofits-energy-

Cone/Rod Response Functions





- **Proteins in the cone/rod cells absorb photons changing the cells membrane potential**
- **The eye <u>only</u> collects 4 types of signals:**
  red, green, blue, and rod

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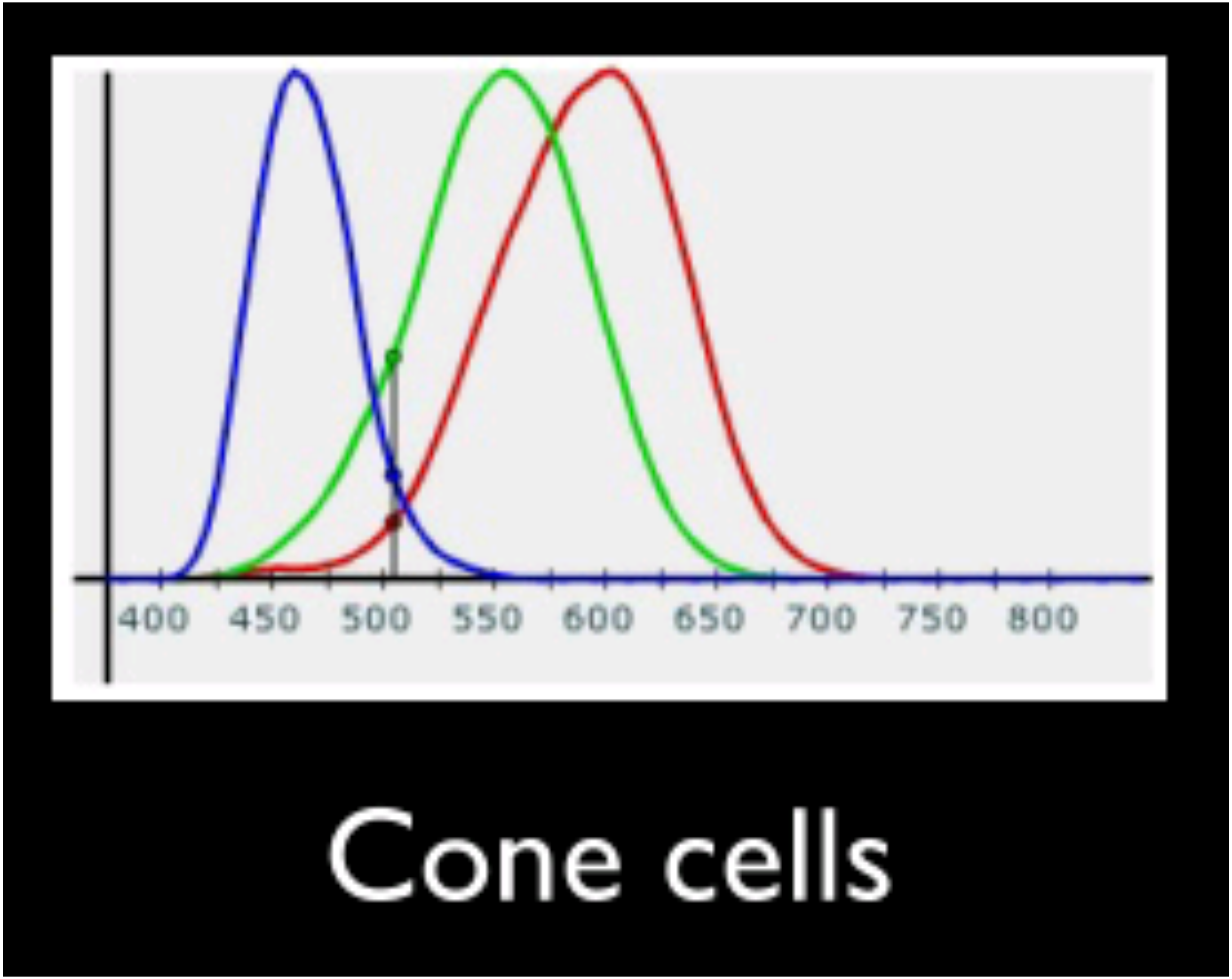
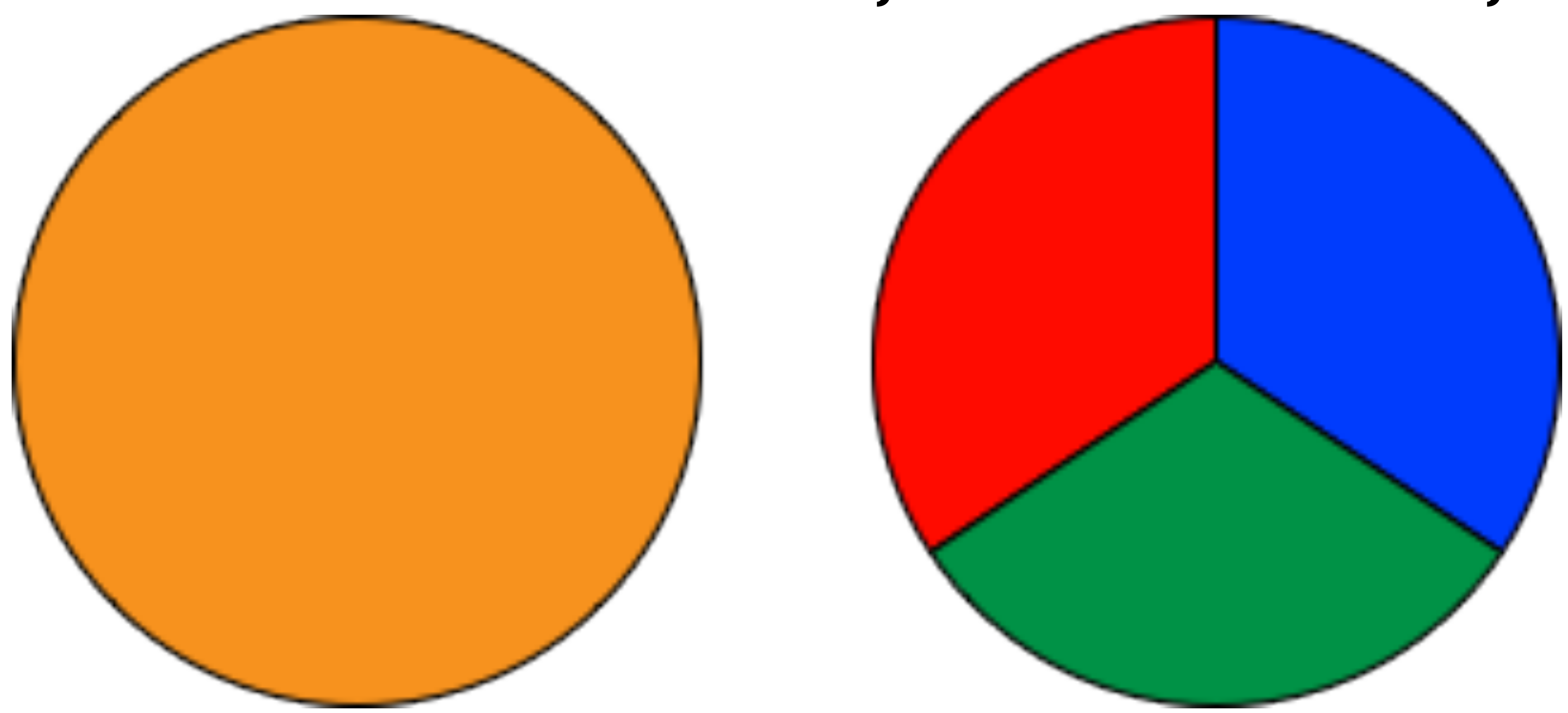


Trichromatic Theory

Color Matching Experiment

- Adjust the brightness of three single wavelength lasers until a human observer “<u>mistakenly</u>” thinks it matches another color C

Lasers: R = 700 nm, G = 546 nm, B = 435 nm



C “=“ R “+” G “+” B

- Humans mistakenly believe that all “colors” are matched by certain combinations of three single wavelength lasers
- Because each of the three cones can only send a single signal

Trichromatic Theory

- Since the human eye works with only 3 signals (ignoring rods), we work with 3 signals for images, displays, printers, etc.

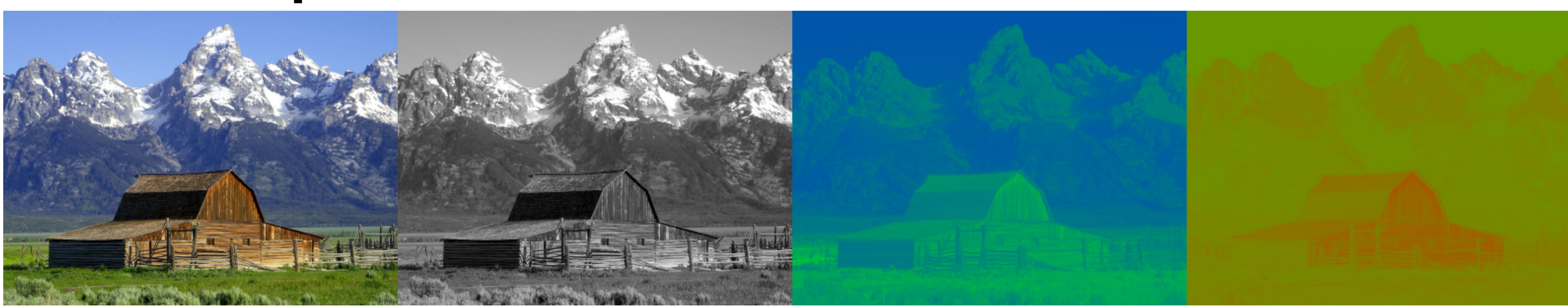
- Image formats store values in the R, G, and B channels
  - The values stored are typically between 0 and 255 (unless its HDR)
  - The relative values give the color, and the overall values give the intensity

- The computer monitor/display can be used to further increase or decrease the overall global image intensity (brightness/darkness)

Dynamic Range

Brightness (Luminance)

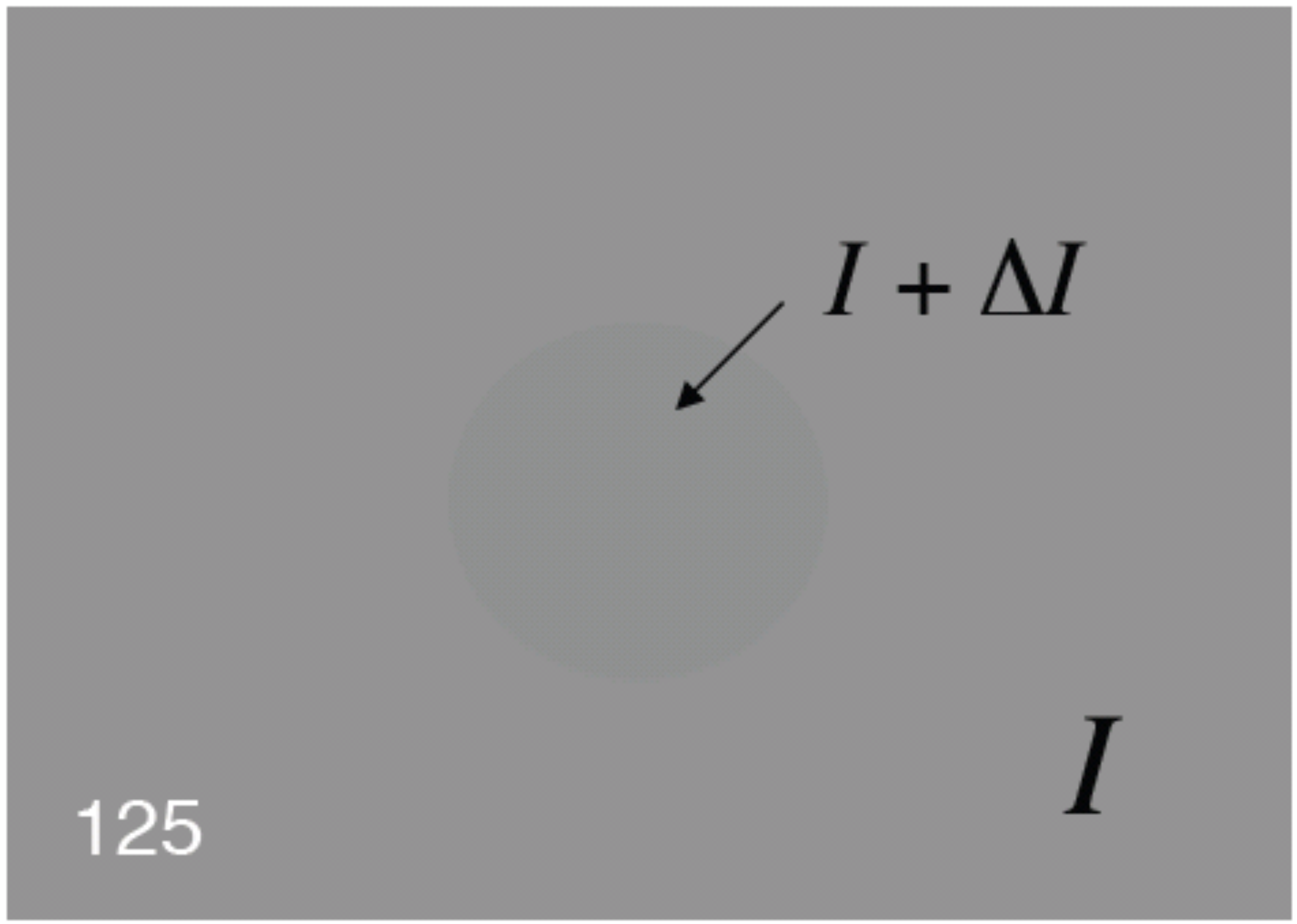
- The human eye is much more sensitive to <u>spatial variations</u> in brightness (gray scale) than to spatial variations in color
- The three images on the right add together to give the image on the left
- Notice which of those three images on the right has the most spatial details!



Original Image = Greyscale + Color 1 + Color 2

Brightness Discrimination Experiment

Can you see this circle?



I is luminance, measured in cd/m^2

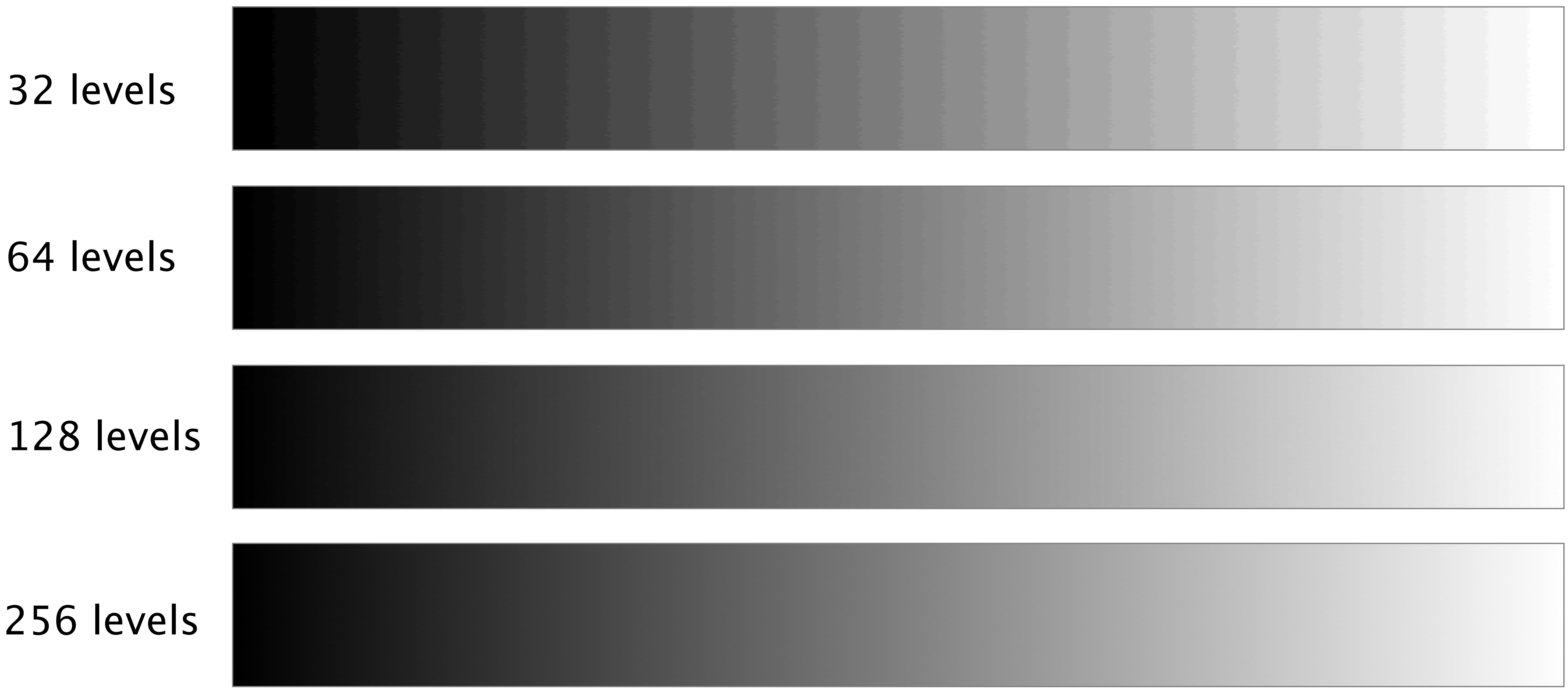
Just noticeable difference

$\Delta I / I \approx K_{Weber} \approx 1 \ldots 2\%$

Weber fraction
Weber's Law

(slide from Bernd Girod)

How many gray levels are required?

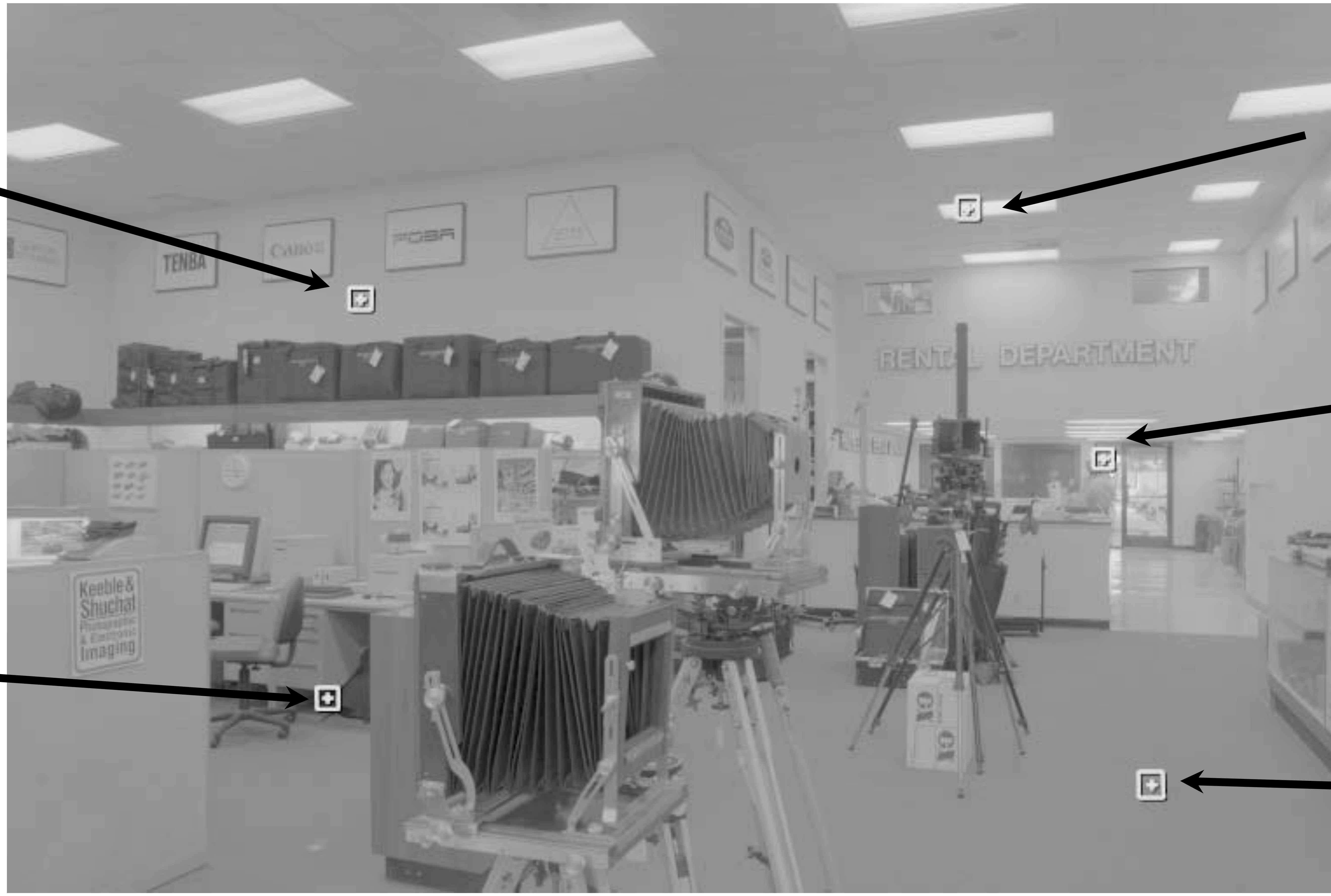


- **Since the human eye can see small changes in brightness, we need many bits for brightness**
- **Otherwise changing the brightness by the smallest amount will be seen as a visual discontinuity**

Dynamic Range (Max/Min)

- World:
  - Possible: 100,000,000,000:1 (from the sun to pitch black)
  - Typical Real World Scenes: 100,000:1
- Human Eye:
  - Static: 100:1
  - Dynamic: 1,000,000:1
    - As the eye moves, it adaptively adjusts exposure by changing the pupil size
- Media:
  - Newsprint: 10:1
  - Glossy print: 60:1
  - Samsung F2370H LCD monitor: static 3,000:1, dynamic 150,000:1
    - Static contrast ratio is the luminance ratio between the brightest white and darkest black within a single image
    - Dynamic contrast ratio is the luminance ratio between an image with the brightest white level and an image with the darkest black level
  - The contrast ratio in a TV monitor specification is measured in a dark room. In normal office lighting conditions, the effective contrast ratio drops from 3,000:1 to less than 200:1

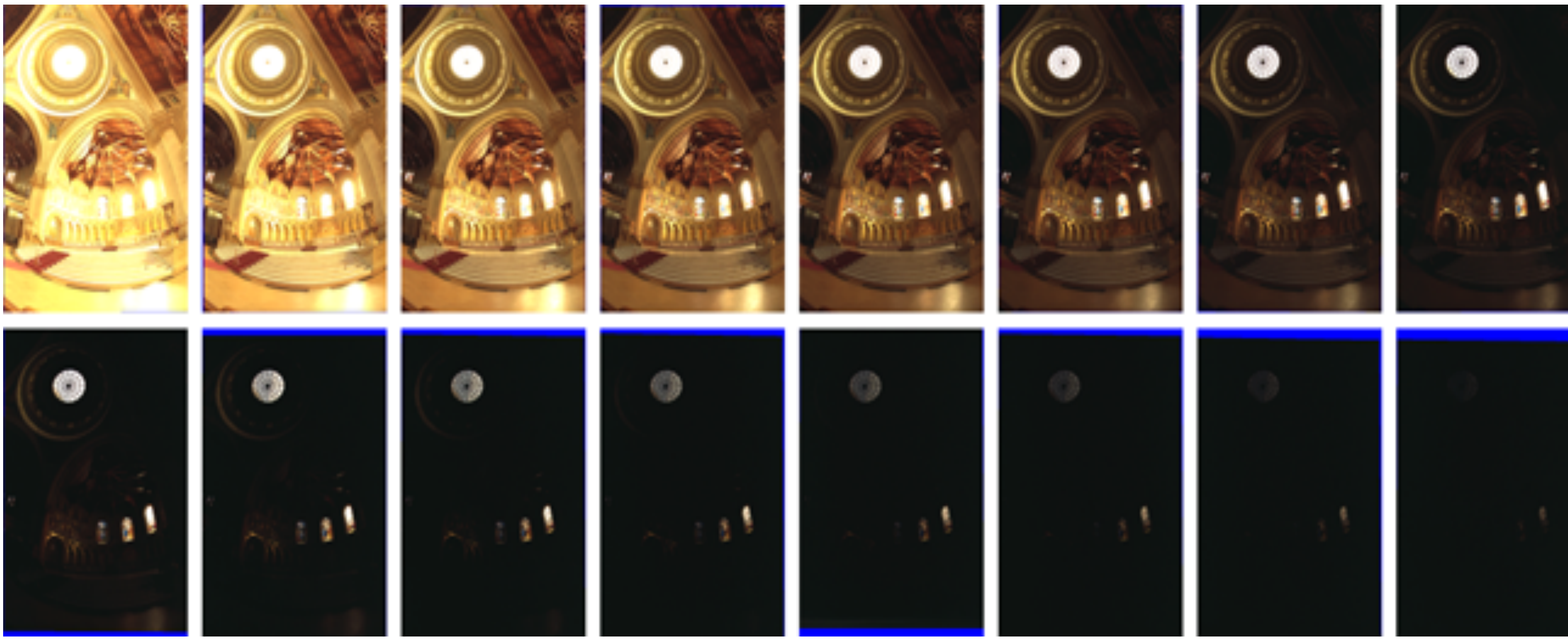
The Real World has a High Dynamic Range



The relative irradiance values of the marked pixels

Dynamic Range

- Sixteen photographs of the Stanford Memorial Church taken at 1-stop increments from 30s to 1/1000s



- No single image captures everything we want in both the darkest and the brightest regions (some pixels are over-saturated and others have no signal at all)

From Debevec and Malik, [High Dynamic Range Photographs]

Tone Mapping

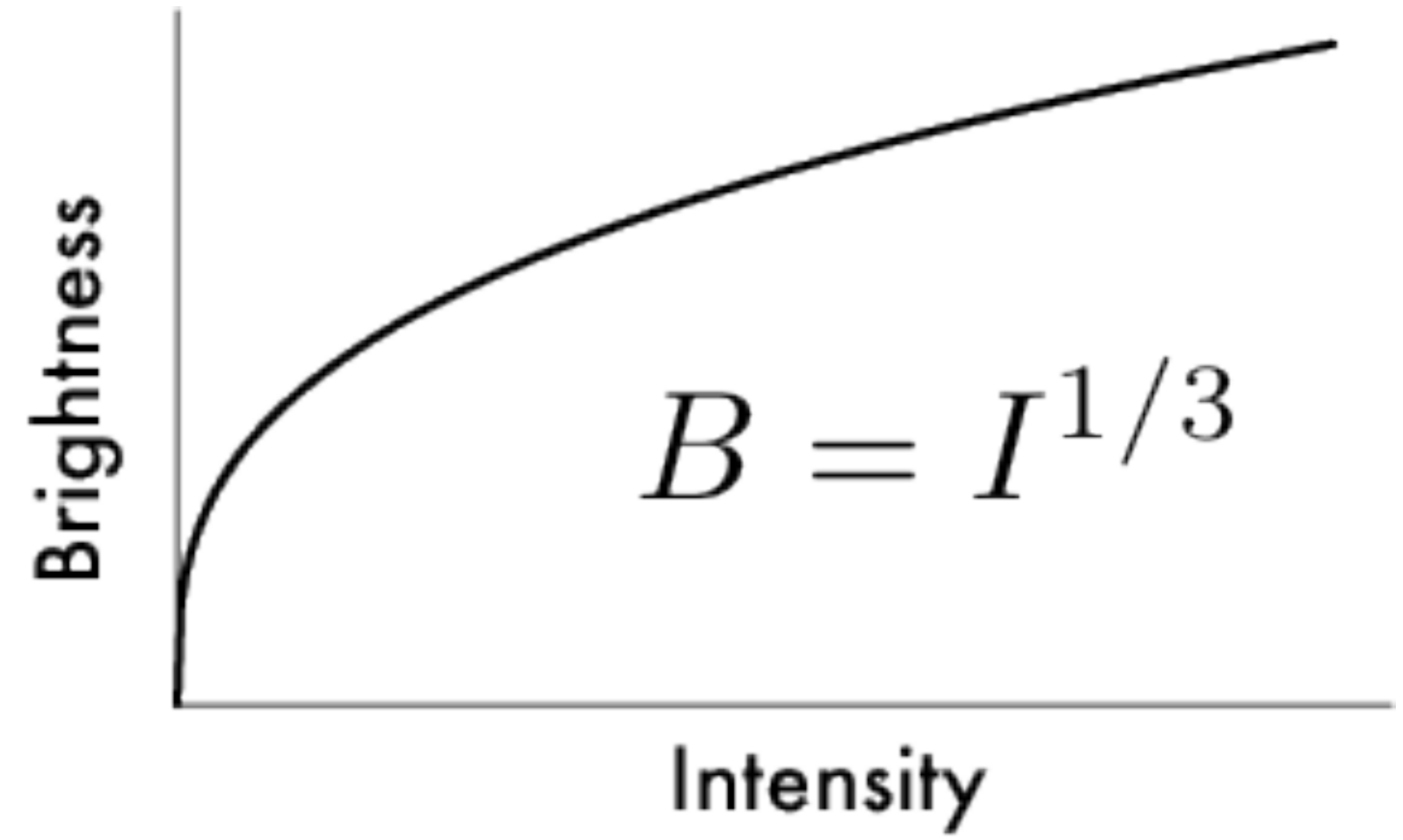
Tone Mapping

- "Compositing" <u>all</u> the information from <u>all</u> the images gives a result with a <u>High Dynamic Range</u> (i.e., 0–X with X > 255)
- Problem: The result contains a higher dynamic range than we can store in the image format (i.e., X > 255)
- Solution #1: Linearly rescale/compress the values so that X=255
  - Small intensity differences are <u>quantized</u> (a range of values map to the same integer), and relative differences are lost
- Solution #2: Logarithmic map to rescale/compress
  - Information is still quantized, but in a more forgiving way considering human "perceptual space"
- Solution #3: Other approaches…
  - E.g., Local operators – map each pixel value based on surrounding pixel values (human vision is sensitive to local contrast)

Human Perception of Intensities

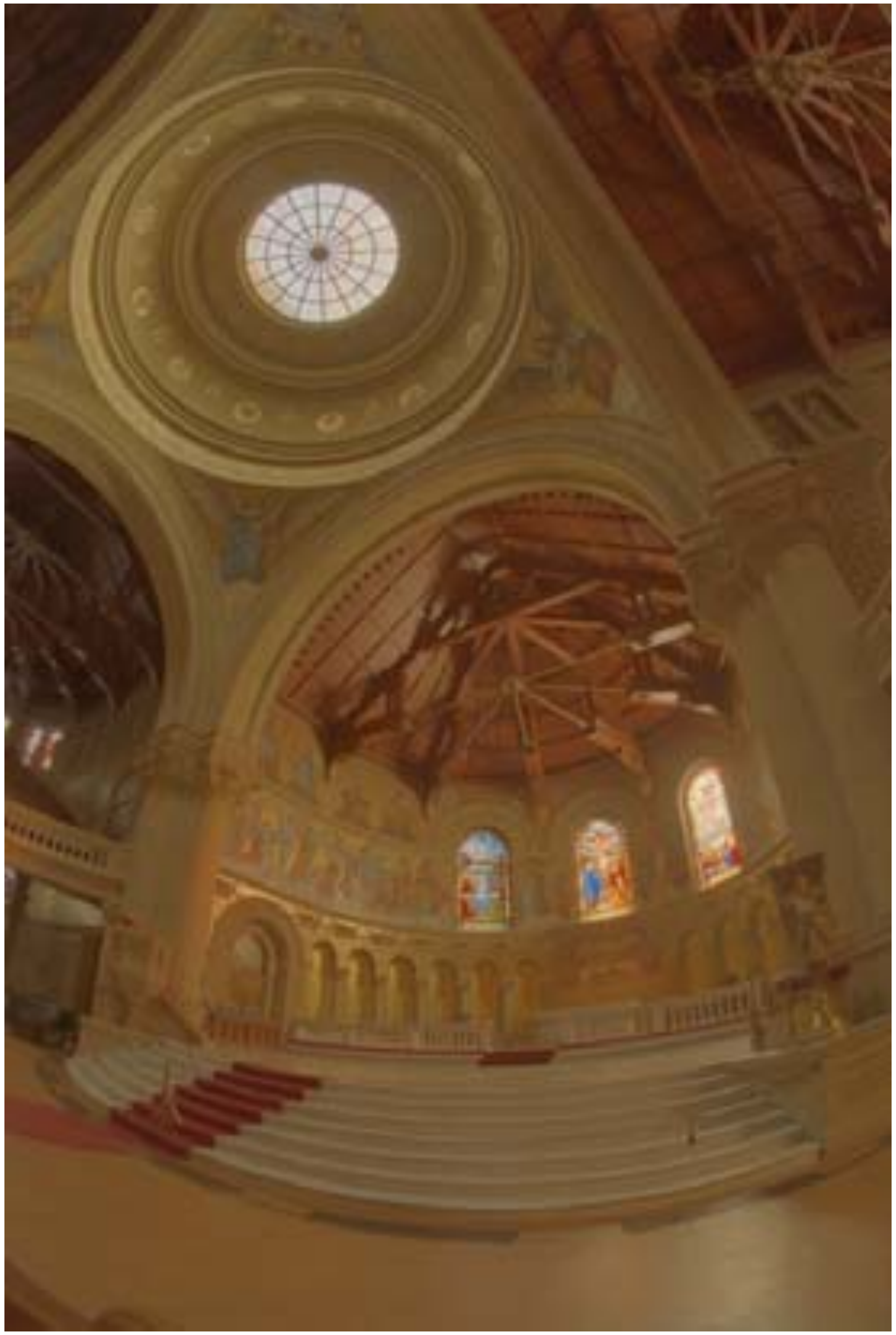
$$S = I^p$$

Sense	Exponent
Brightness	0.33
Loudness	0.60
Length	1.00
Heaviness	1.45



- **Brightness** intensity differences are better perceived by humans at lower light intensities
- A logarithmic compression uses more of the display's brightness resolution for the lower intensities in the image
- Thus less of the display's resolution is used on the higher intensities
- This causes more quantization in the higher intensities of the image than in the lower intensities of the image (and is more optimal for human consumption)

Tone Mapping



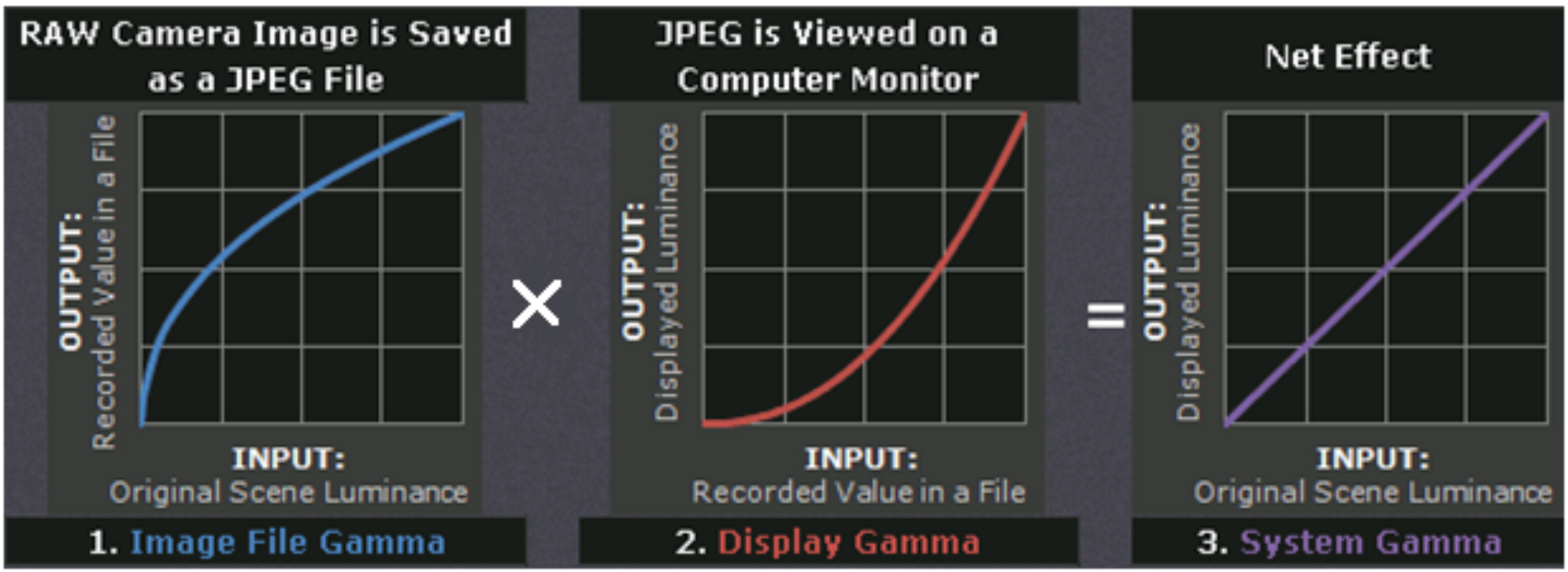
Linear map

Logarithmic map

Gamma Encoding and Correction

- Maximize the use of the bits relative to human perception
- More bits are allocated to the darker regions of the image than to the lighter regions

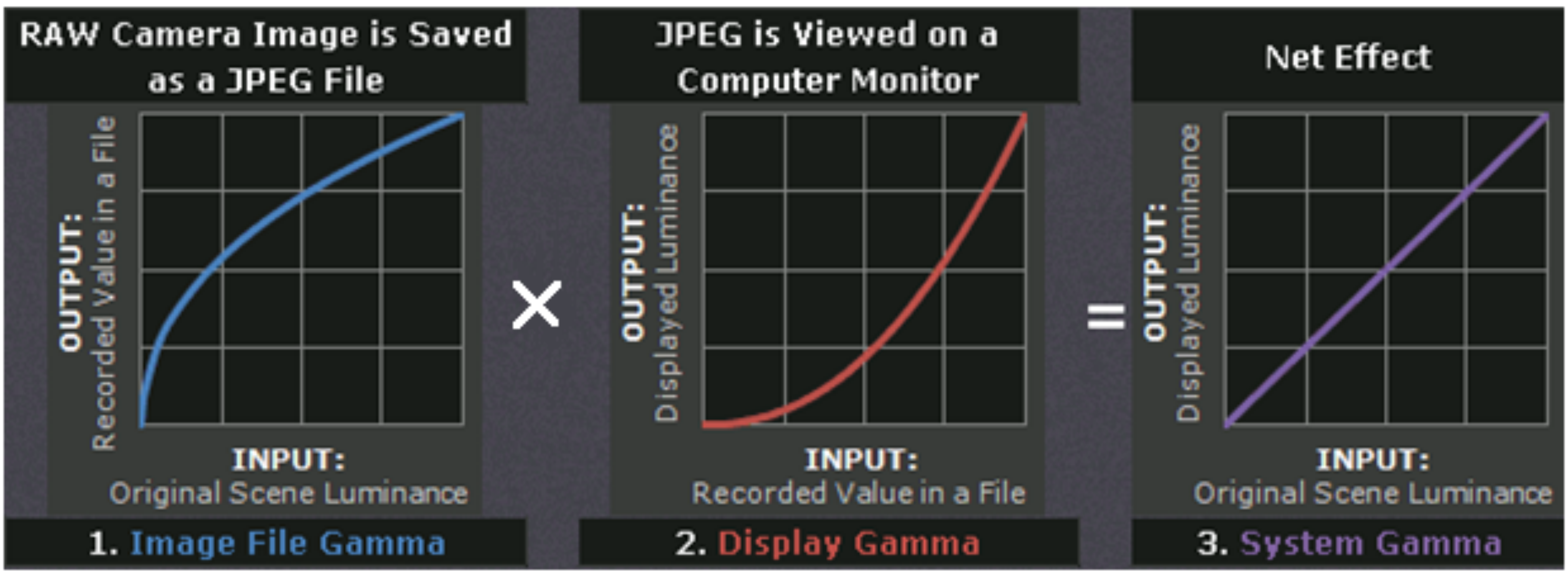
- Gamma correction is applied to the gamma encoded (compressed) images to convert them back to the original scene luminance



UNDERSTANDING GAMMA CORRECTION

LONG FORM #1

- **Summarize how gamma correction works (about 250-500 words).**



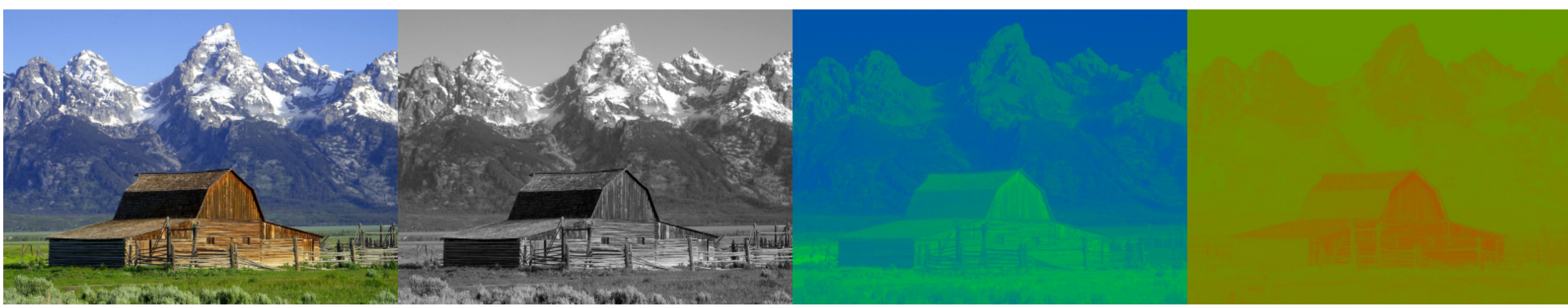
UNDERSTANDING GAMMA CORRECTION

Color Spaces

Luminance and Chrominance (YUV)

- Represent an RGB color via a single luminance and two chrominance channels
- Black and White televisions used Y only
- Can compress more aggressively in U & V than in Y

$$\begin{bmatrix} Y \\ U \\ V \end{bmatrix} = \begin{bmatrix} .299 & .587 & .114 \\ -.14713 & -.28886 & .436 \\ .615 & -.51499 & -.10001 \end{bmatrix} \begin{bmatrix} R \\ G \\ B \end{bmatrix}$$



Original Y U V

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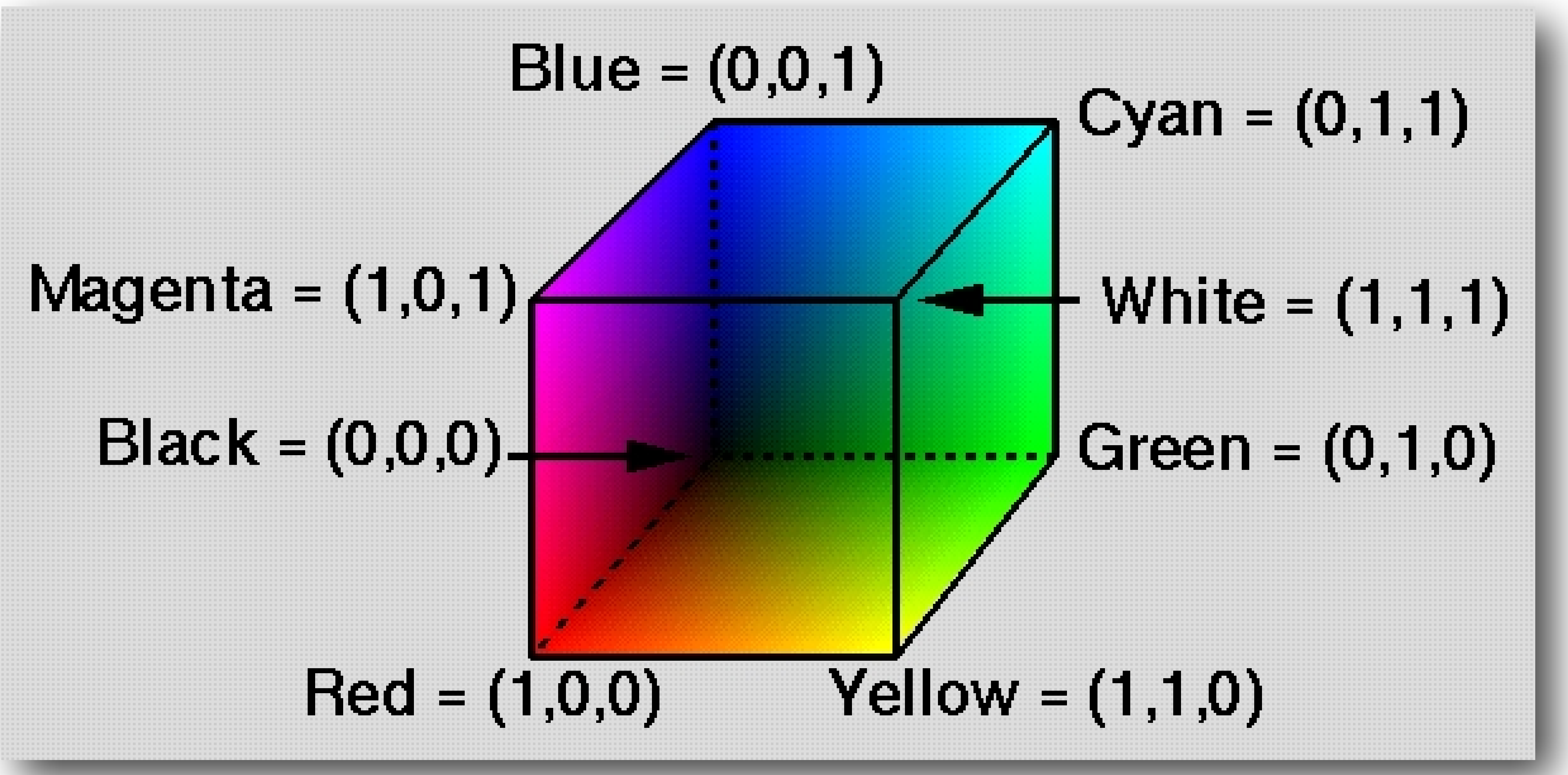
$$\begin{bmatrix} Y \\ U \\ V \end{bmatrix} = \begin{bmatrix} .299 & .587 & .114 \\ -.14713 & -.28886 & .436 \\ .615 & -.51499 & -.10001 \end{bmatrix} \begin{bmatrix} R \\ G \\ B \end{bmatrix}$$

cs148.staff@gmail.com (#4)

$$\begin{bmatrix} Y \\ U \\ V \end{bmatrix} = \begin{bmatrix} .299 & .587 & .114 \\ -.14713 & -.28886 & .436 \\ .615 & -.51499 & -.10001 \end{bmatrix} \begin{bmatrix} R \\ G \\ B \end{bmatrix}$$

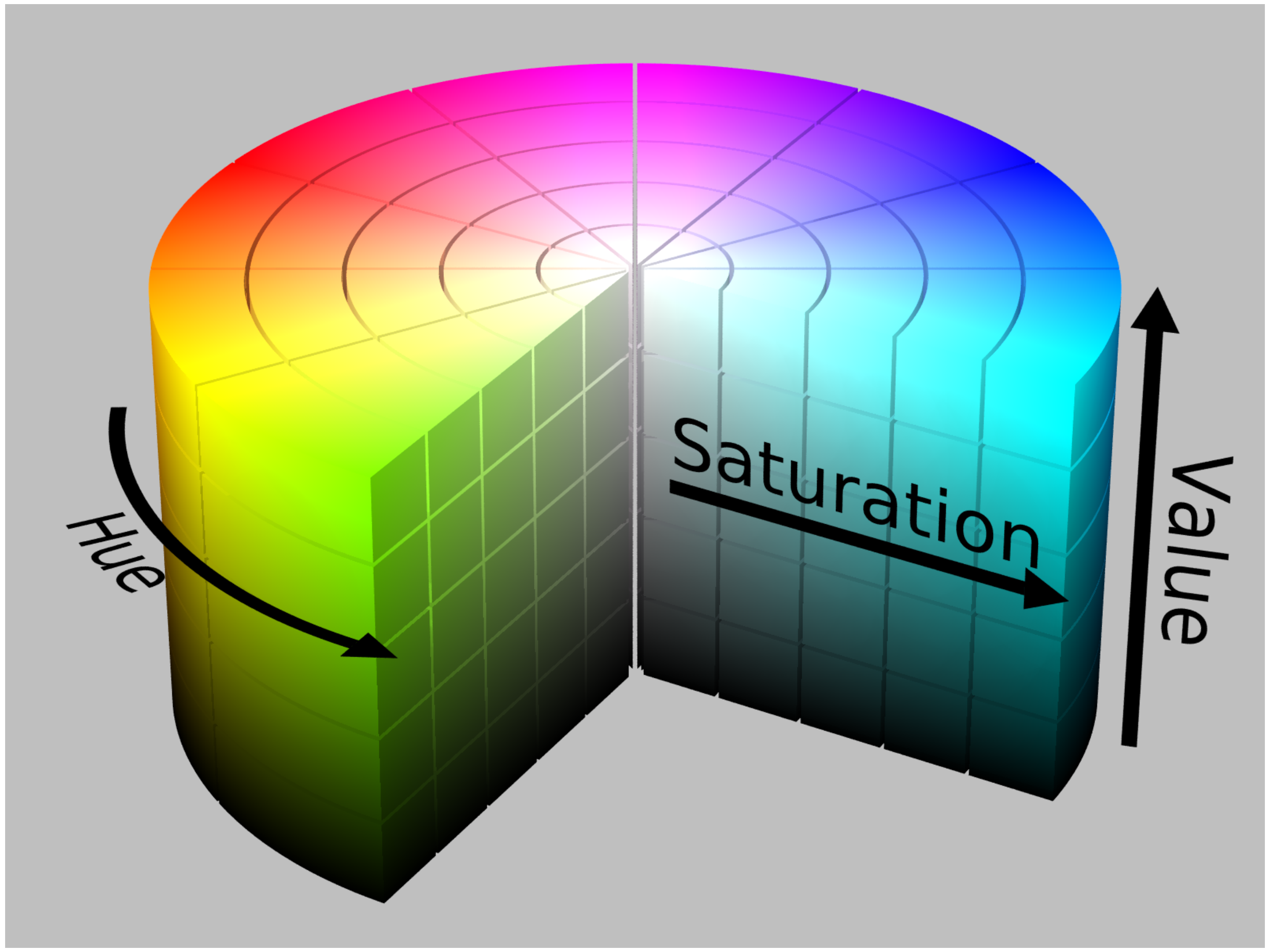
RGB Color Cube

- Map each primary color in the RGB color space to the unit distance along the x, y, z axes
  - Black at (0,0,0), white at (1,1,1)
  - The color cube represents all possible colors



Cylindrical HSV Color Space

- HSV: Hue, Saturation and Value
- Hue: rainbow of colors (“wavelength”)
- Saturation: distribution of intensity for a particular color
- Value: relative lightness or darkness of a particular color
- great for <u>user interfaces</u>, “color picker”



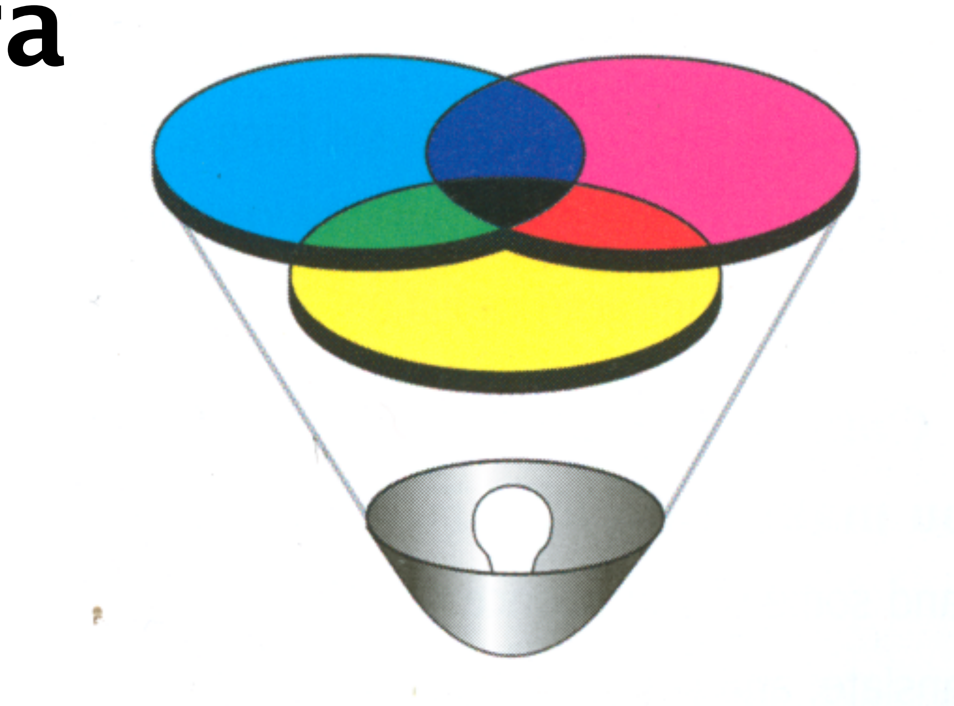
Additive vs. Subtractive Color Spaces

Additive:

- Add spectra
  - wavelength-by-wavelength
- Superimposed colored lights
- Computer display
- R + G + B = white

Subtractive:

- *Multiply* transmittance/absorption spectra
  - wavelength by wavelength
- Sequence of color filters
- Layered pigments (printing)
- R + G + B = black



(London, Stone and Upton)

Printers

Printers – subtractive CMY color model

- Cyan, Magenta, Yellow – the three primary colors of the subtractive color model
- Partially or entirely masking/filtering (absorbing) colors on a white background
- The ink reduces the light that would otherwise be reflected
- Equal mixtures of C,M,Y should (ideally) produce all shades of gray

C
M
Y

Printers – subtractive CMYK color model

- Advantages of using black ink:
  - Most fine details are in printed with the Key color (=K=black)
  - Less dependency on (perfectly) accurate color alignment
  - Mixtures of 100% C, 100% M and 100% Y do not give perfect black in practice
  - Reduce bleeding and time to dry
  - Save colored ink

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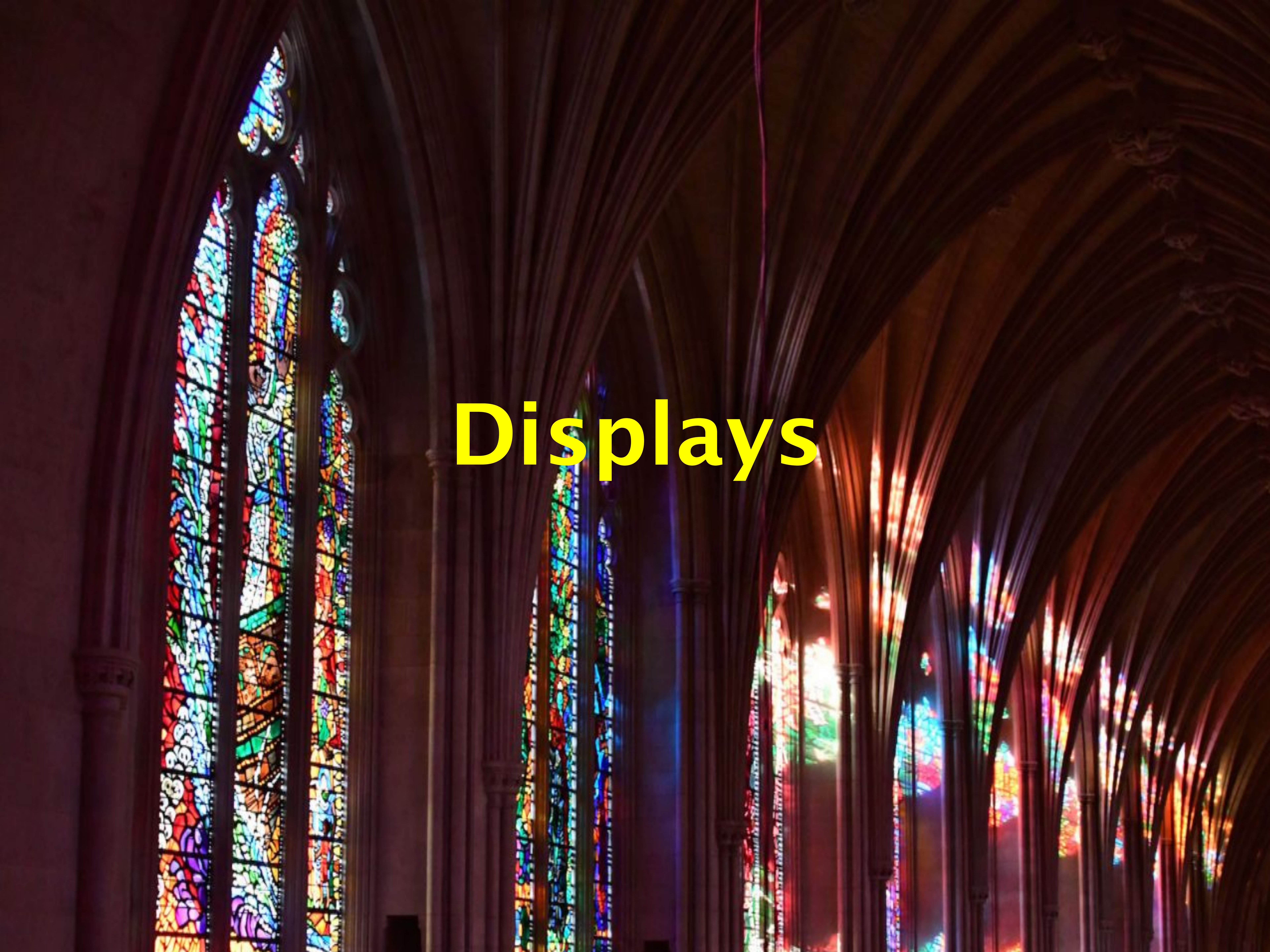
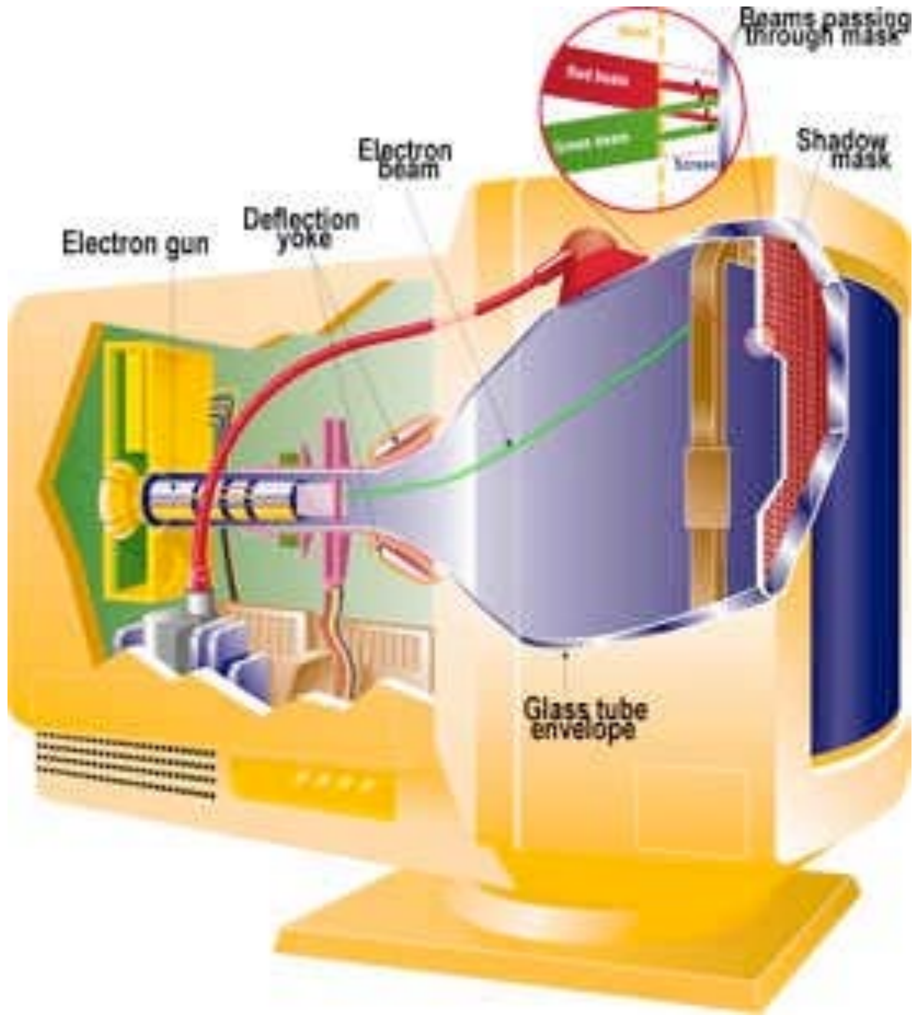
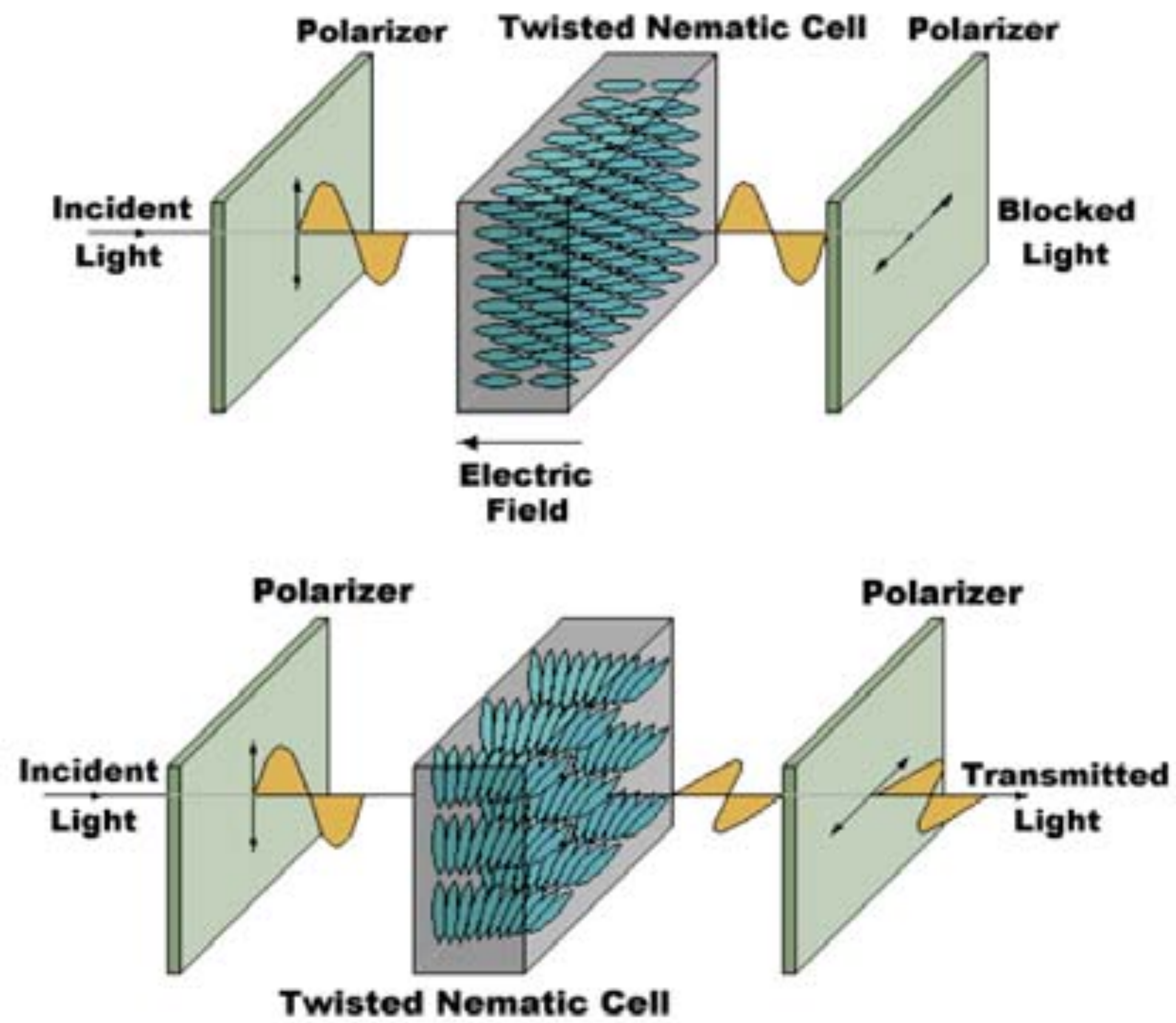
Displays



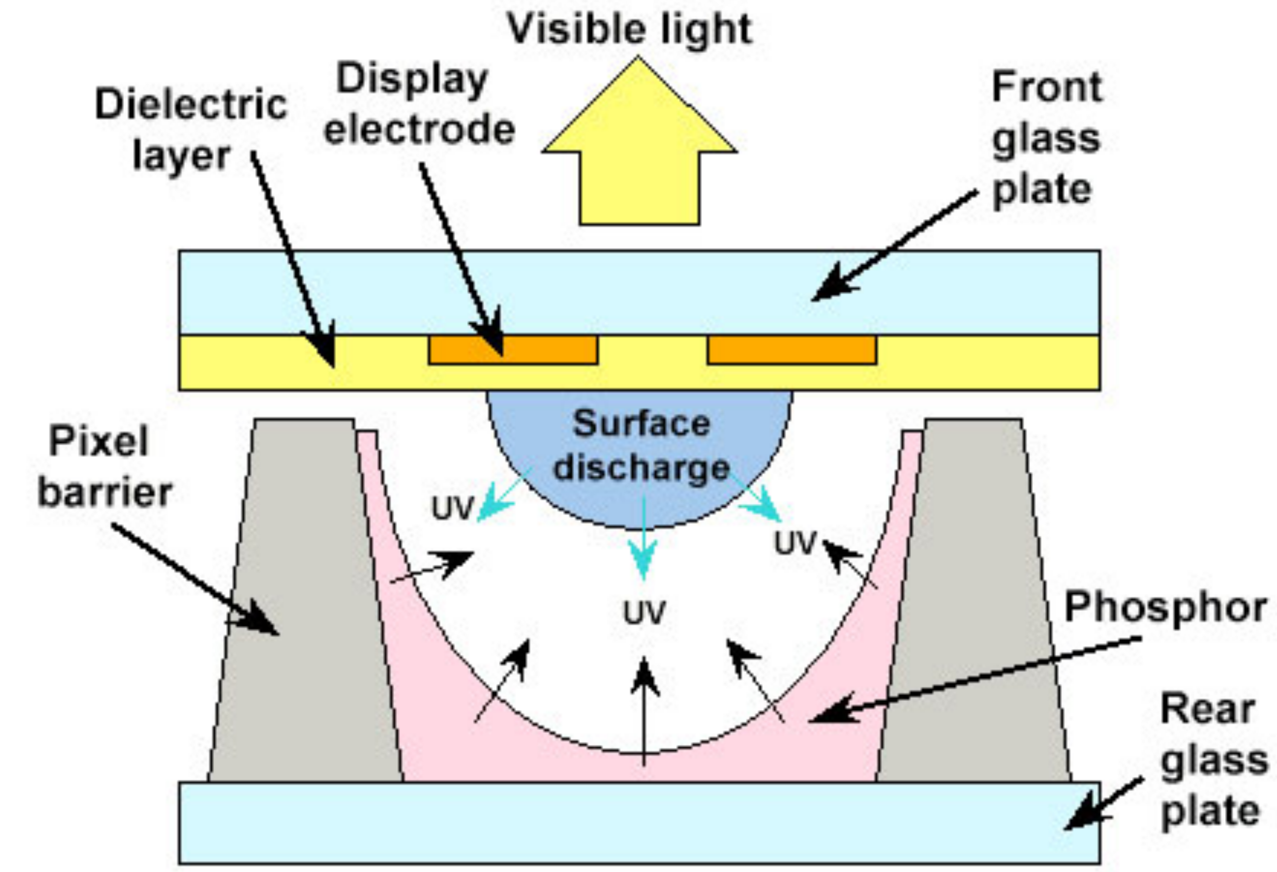
Displays



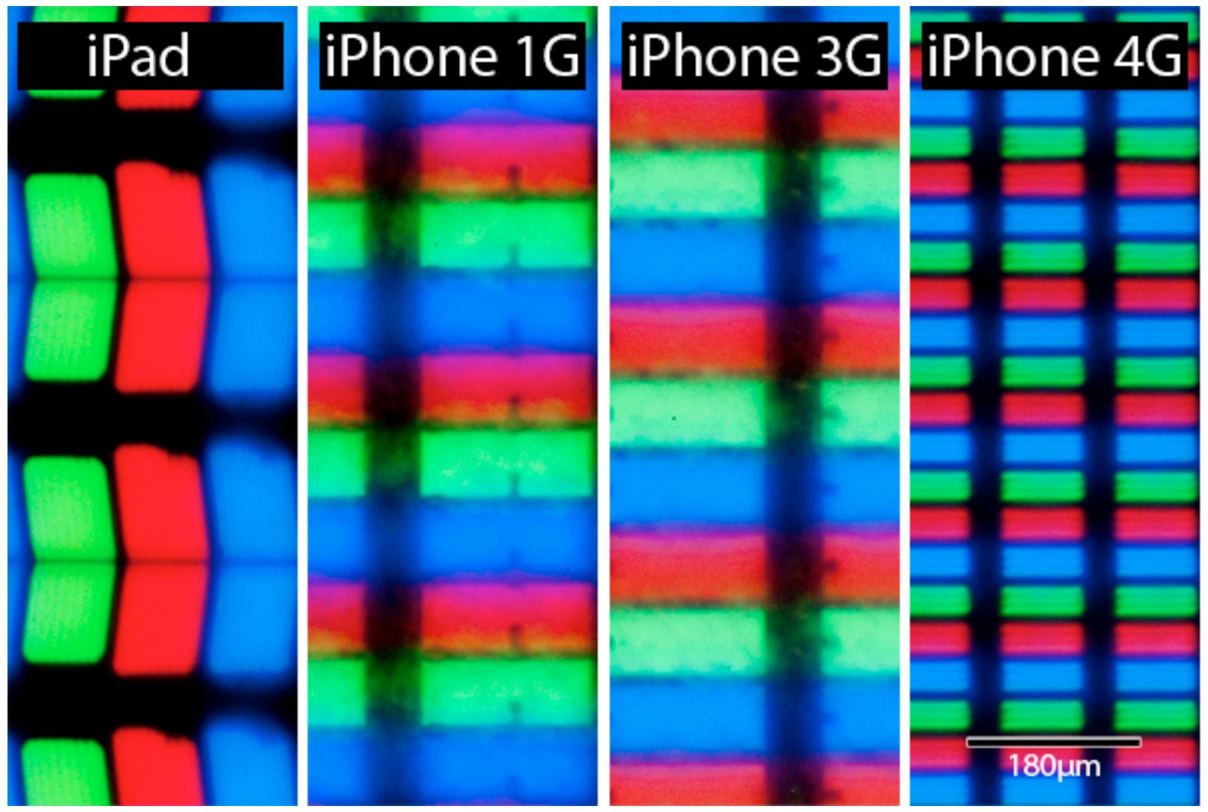
cathode ray tube (CRT)



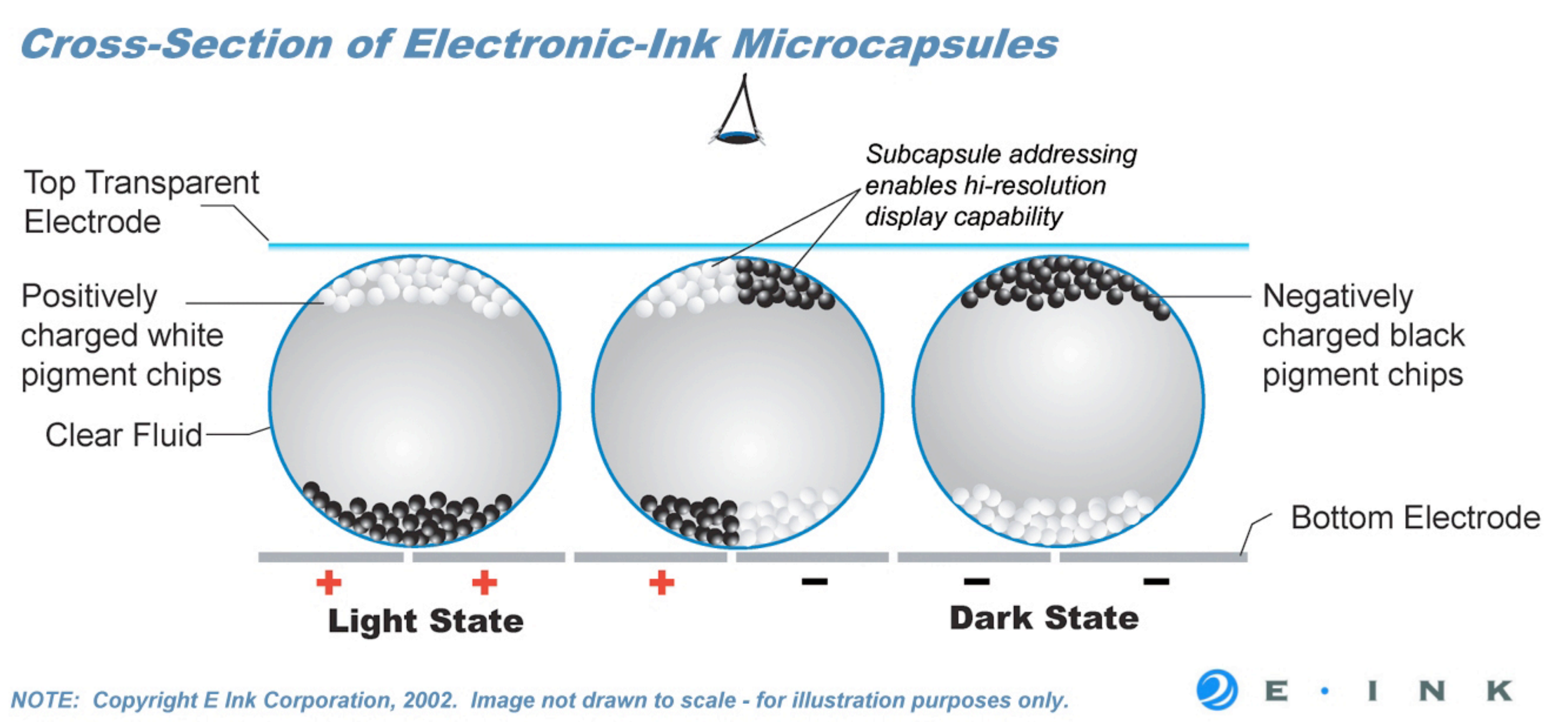
liquid crystal display (LCD)



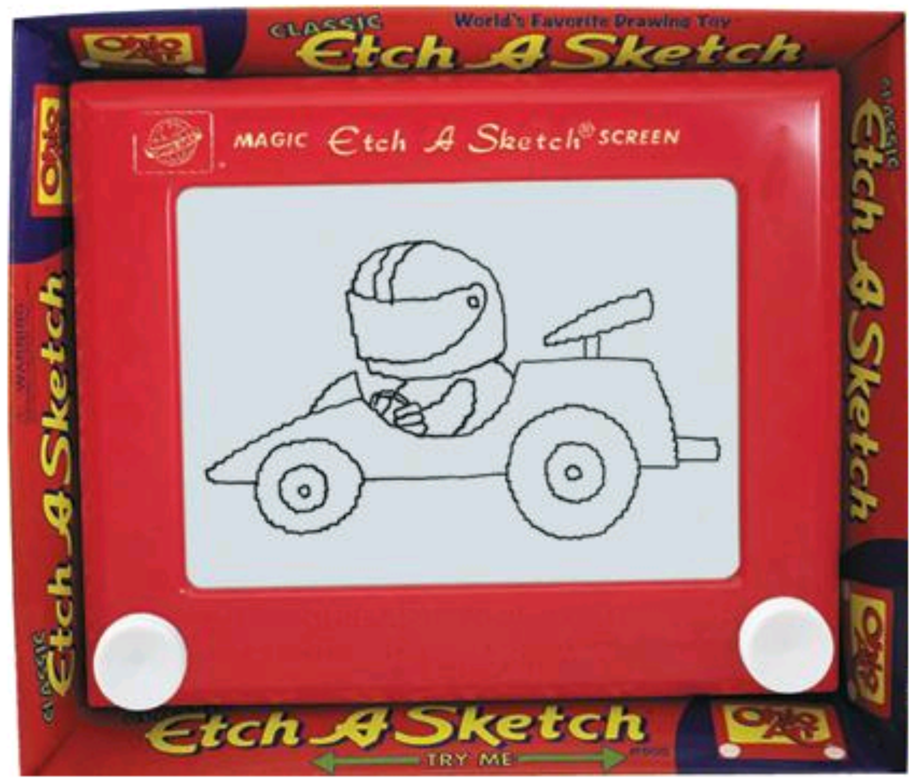
plasma



iPhone/iPad LCD



Electronic ink,
ebook readers



Resolution Matters

Date	Format and Technology
1980	1024 x 768 x 60Hz, CRT
1988	1280 x 1024 x 72Hz, CRT
1996	1920 x 1080 x 72Hz, HD CRT
2001	3840 x 2400 x 56Hz, active LCD

(K. Akeley)

- High-definition television (HDTV)
  - 1280x720
  - 1920x1080
- Ultra-high-definition television (UHDTV)
  - 3840x2160
  - 7680x4320 (Super Hi-Vision, developed by NHK (Japanese Broadcasting Co.))
  - 15360x8640

Distance Matters

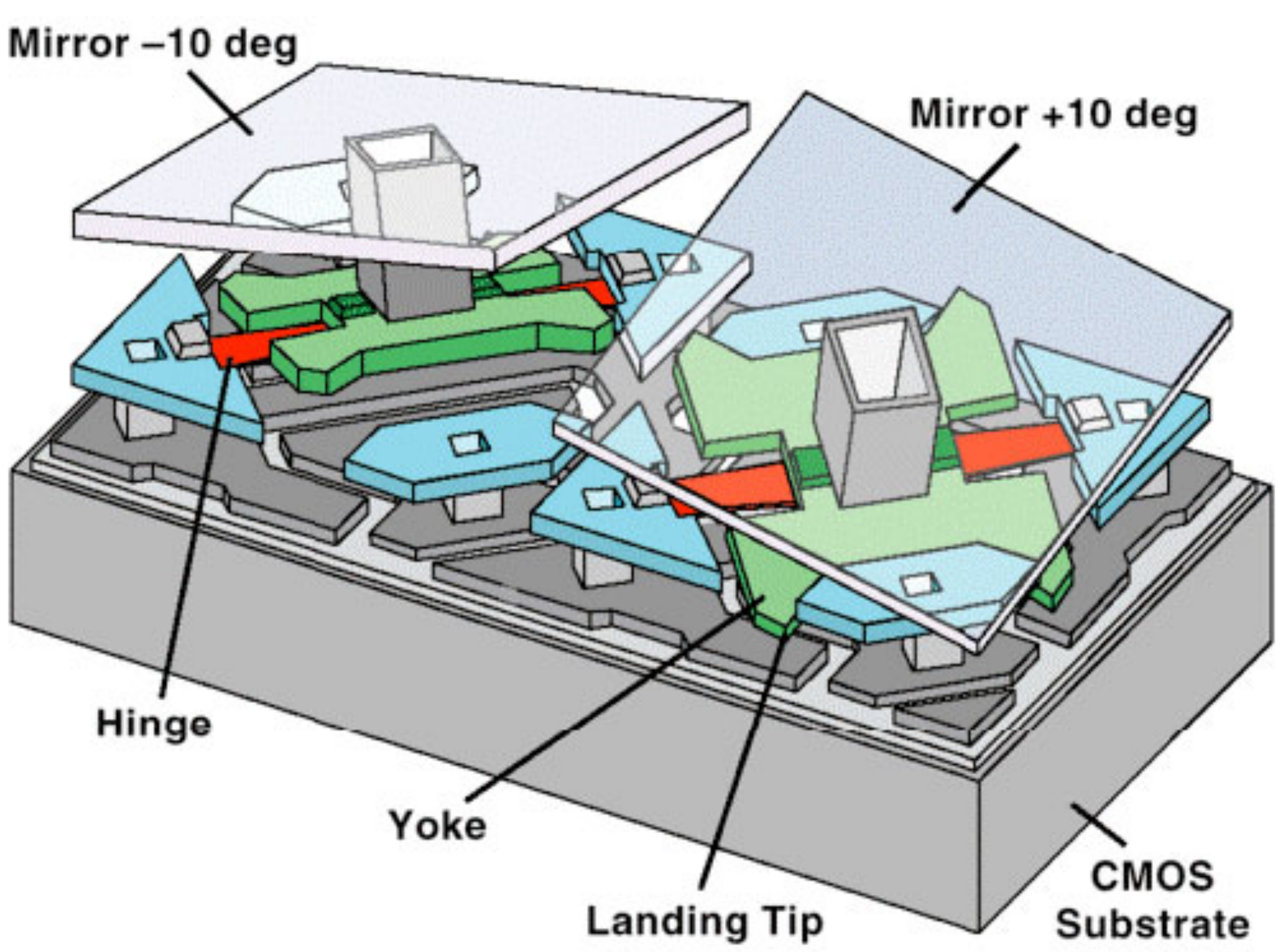
- A lower number of pixels per inch is acceptable for a cinema screen
- People sit much farther from the screen as compared to a computer monitor
- The number of pixels falling into a unit visual angle of the eye is comparable between cinema screens and computer screens given the distance of the observer

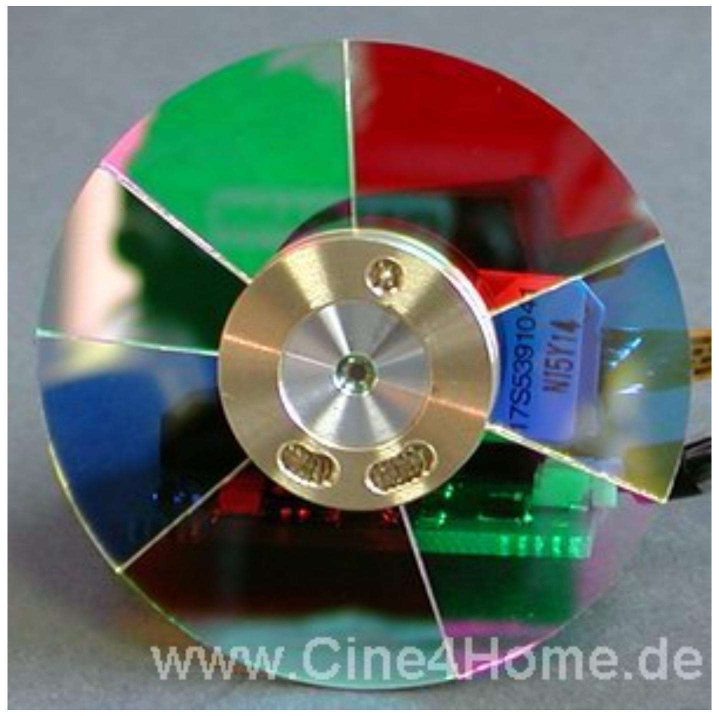
Christie CP2210 DLP
digital cinema projector

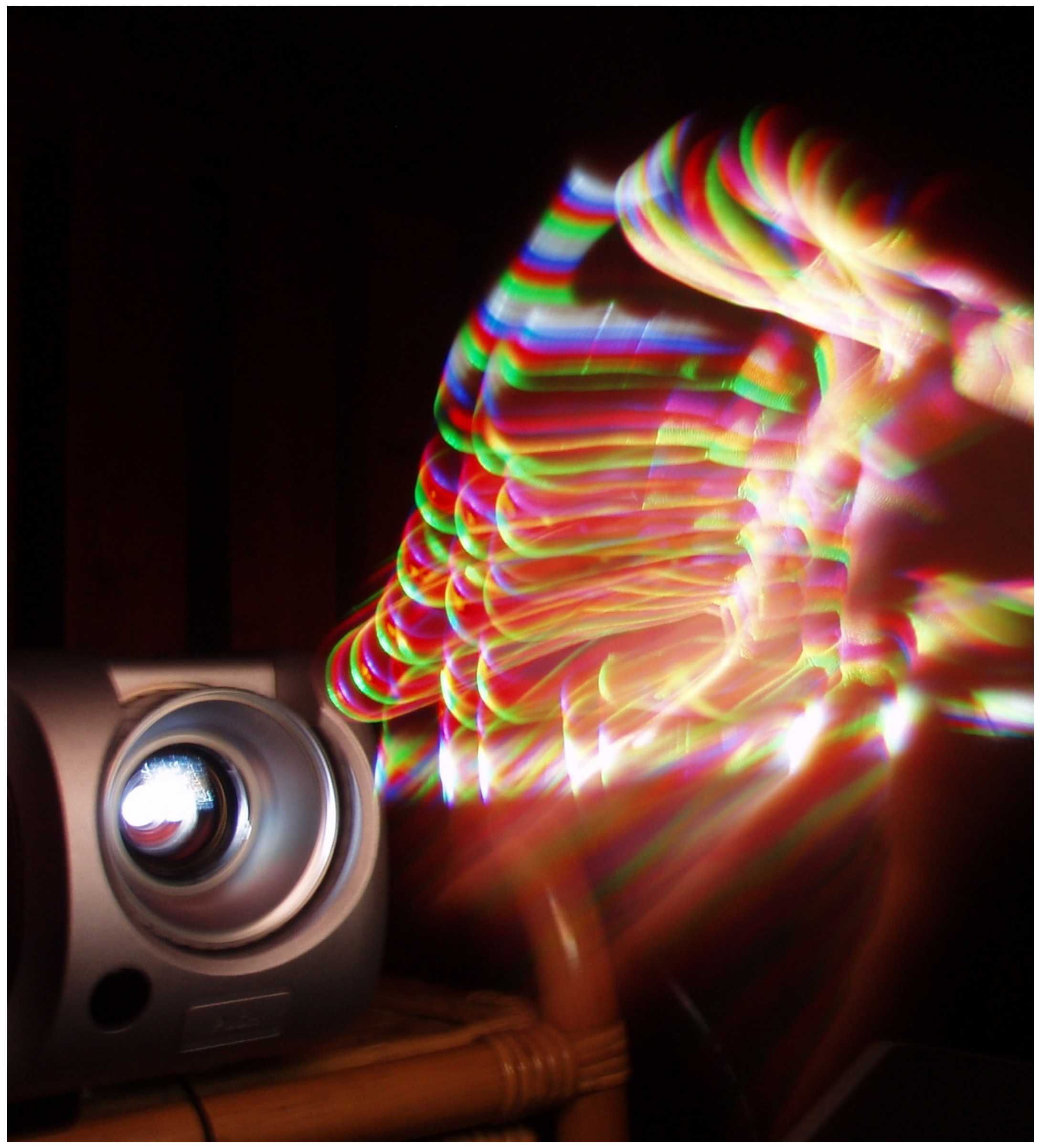
Resolution: 2048x1080
Size: 13.7 m diagonal (4.29 dpi)

Projectors

- Projectors remove the physical limitations of screen sizes, making them suitable for very large screens such as those in cinemas
- A Digital Micro-Mirror Device (DMD) is the core component in Digital Light Processing (DLP) projectors
- Each mirror corresponds to one pixel
- A mirror has two states. It can either reflect the light into or out of the “pupil” of the projector
- Rapidly toggling a mirror between these two orientations produces grayscales, controlled by the ratio of on-time to off-time







LONG FORM #2

- **Tell me about state of the art projector technology (500+ words)**