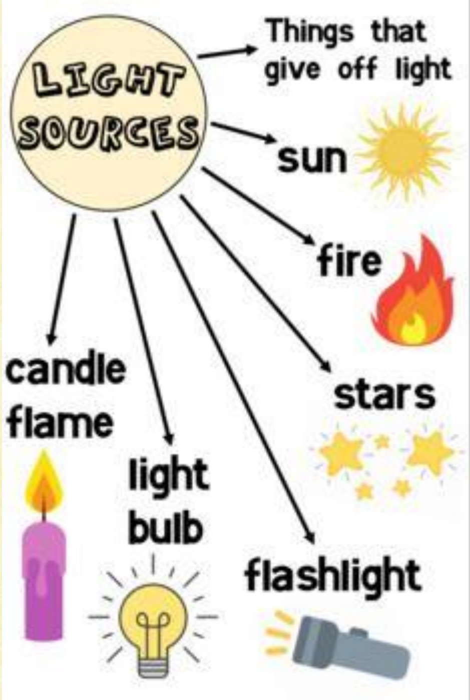
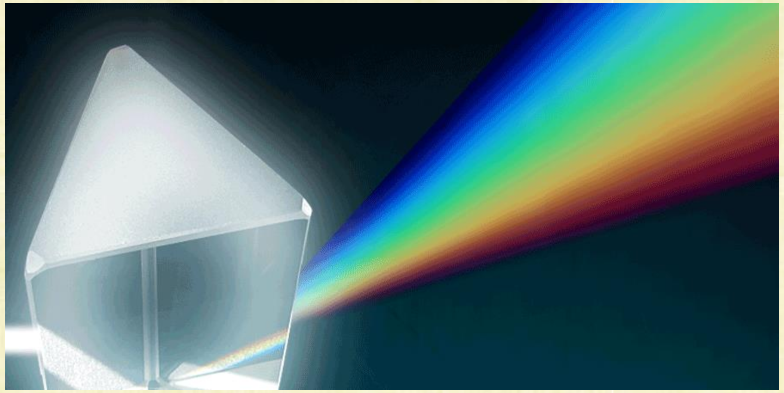
Working with Light

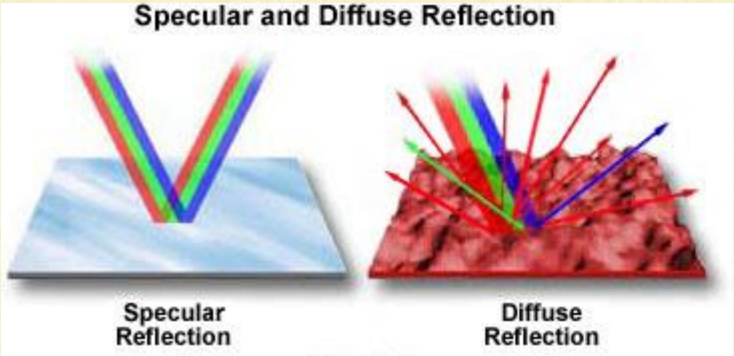
Working with Light for Computer Graphics



Physics/Optics:

- Light is emitted from a light source
  - e.g. the sun, a light bulb, computer monitor, cell phone, etc.
- That emitted light impacts various objects, where it may be reflected or absorbed
  - This reflection/absorption modifies the light
    - e.g. creating color, brightness, dullness/shininess, highlights, etc.
- In addition, light may pass (transmit) through a material and (in doing so) be bent, scattered, etc.
  - e.g. prism, stained glass windows, water, etc.





Working with Light for Computer Graphics

Human Perception:

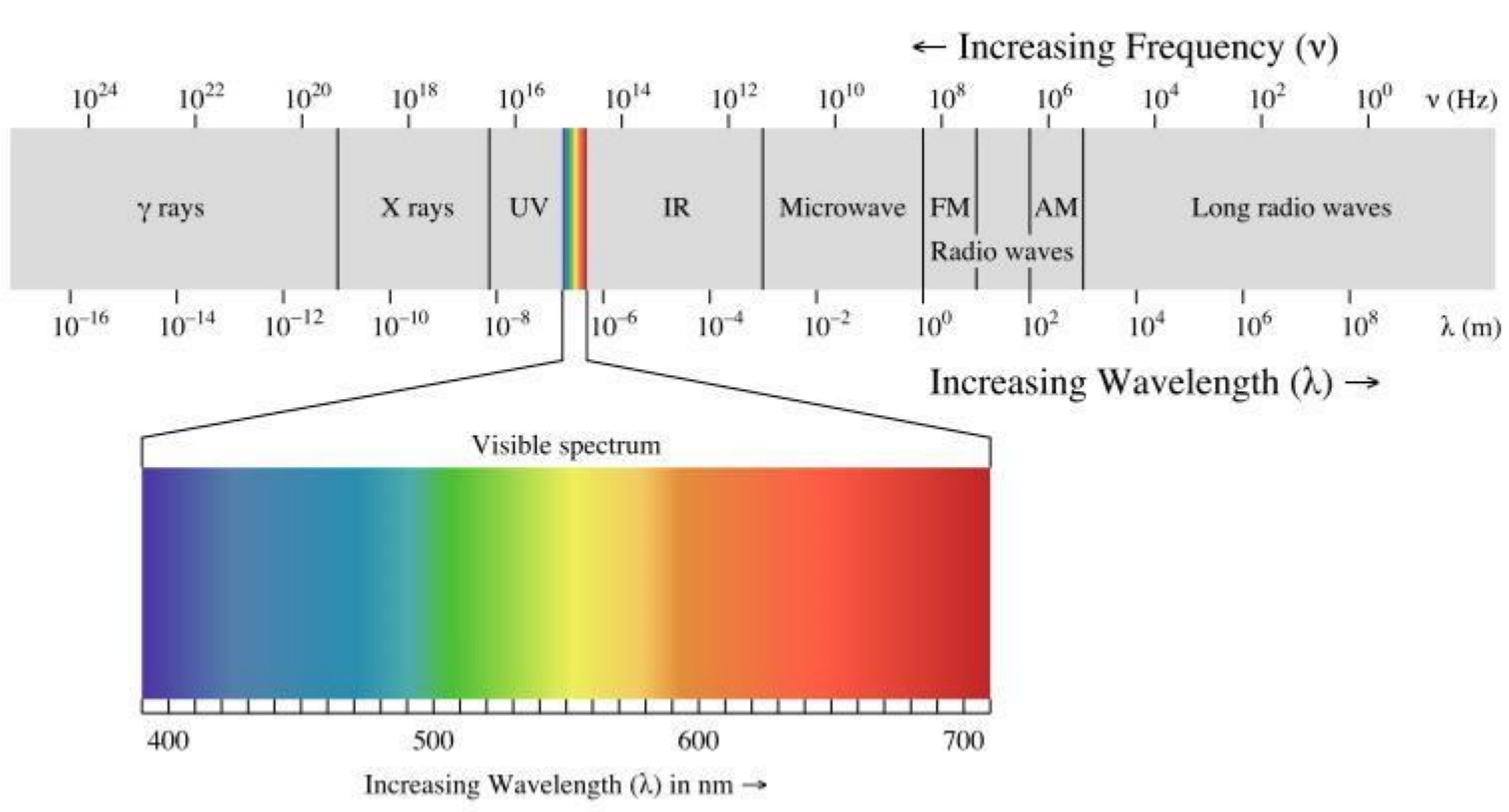
- Eventually, some light enters your eyes creating a signal
- Your brain creates an image based on the signals it gets from your eyes

Software/Hardware:

- Understanding the physics of light (i.e. optics) is important, in order to be able to work with it
- Understanding human perception allows for MANY optimizations/simplifications in both software/hardware

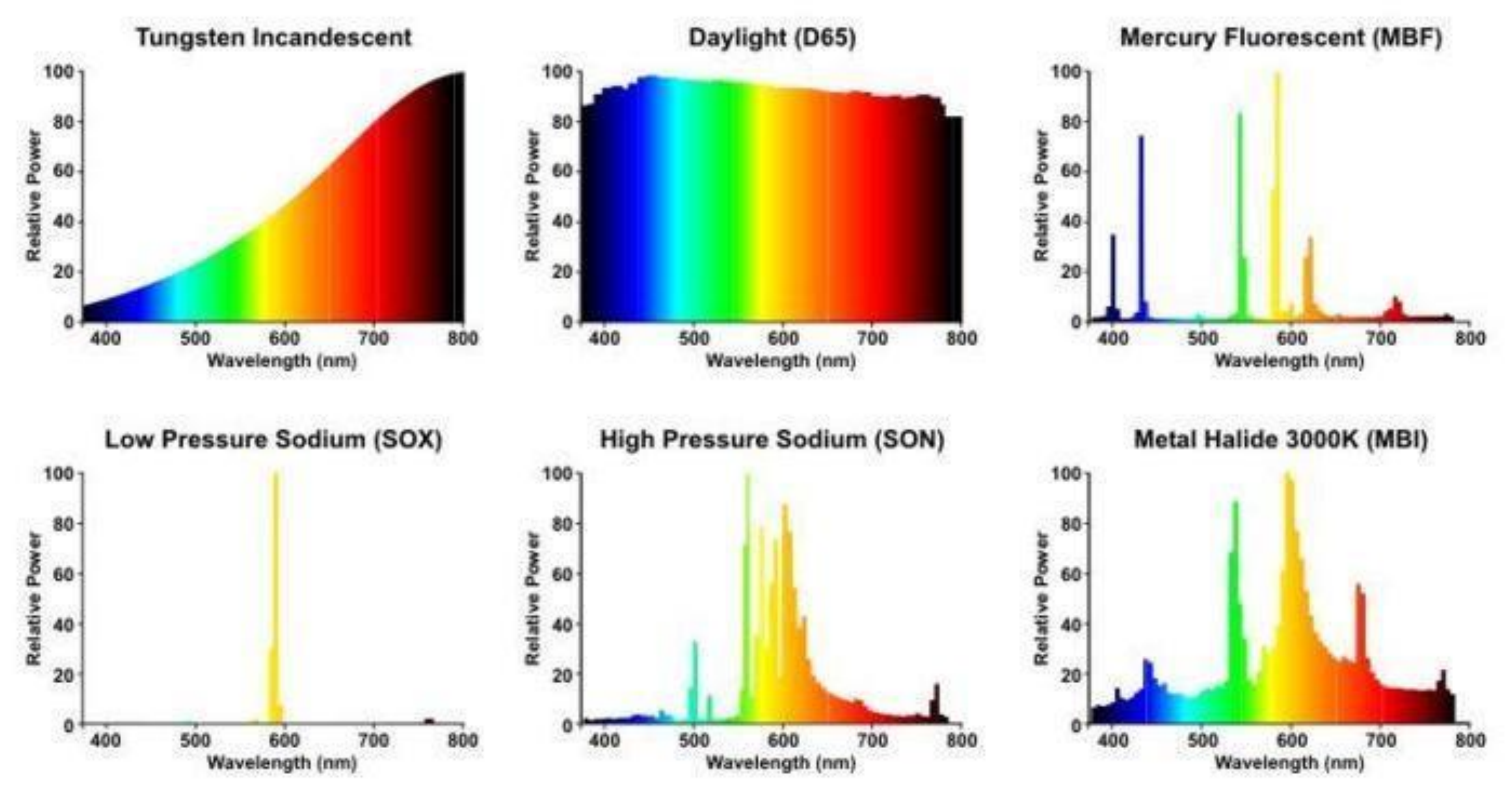
- The images we create ARE NOT intended to duplicate reality, only to fool humans into believing such

Electromagnetic Spectrum



The human eye can only see wavelengths between about 400 nm to 700 nm, so we focus on those

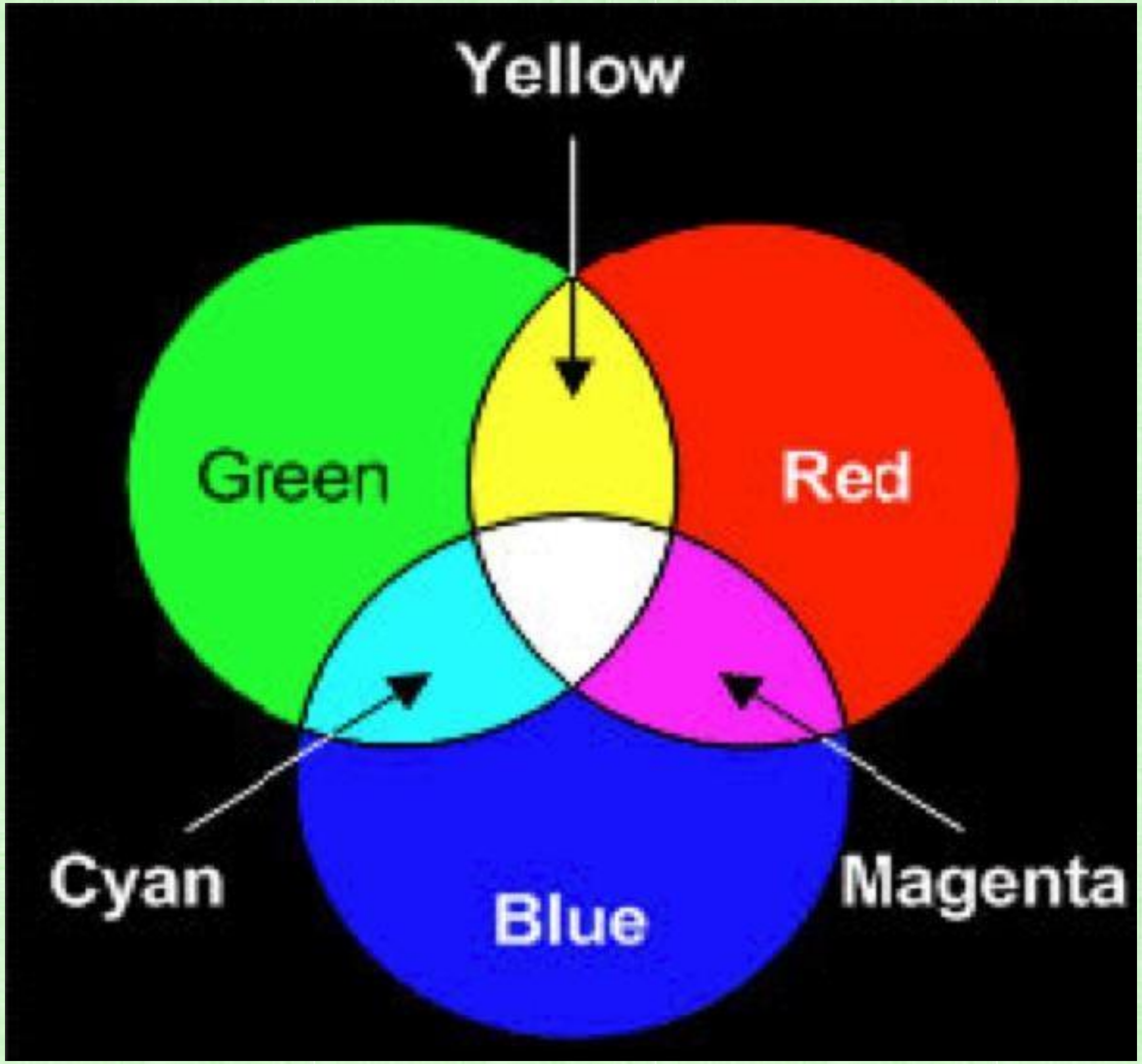
Relative Power Distribution of Lights



Relative Power Distribution of Lights

Light Source	Spectrum Type	Peak Wavelengths (nm)	Color Rendering Ability	Dominant Color(s)	Applications
Tungsten Incandescent	Broad, continuous	Peaks in the red-yellow	Excellent	Warm white to yellow-red	Residential lighting, photography
Daylight (D65)	Broad, relatively uniform	Evenly spread across 400–700 nm	Excellent	Natural daylight	Color-critical tasks, outdoor lighting
Mercury Fluorescent (MBF)	Spiky, narrow peaks	Peaks at 435, 546, 578 nm	Moderate	Green, yellow	Office lighting, industrial areas
Low Pressure Sodium (SOX)	Narrow, very limited band	Peak at 589 nm	Poor	Yellow	Streetlights, parking lots
High Pressure Sodium (SON)	Broad, with strong peaks	Peaks at 589, 600 nm	Moderate	Yellow, orange	Highway lighting, industrial spaces
Metal Halide 3000K (MBI)	Broad, with peaks	Peaks in blue, green, red	Good	Neutral white	Stadiums, retail, high-intensity needs

Adding Light Energy

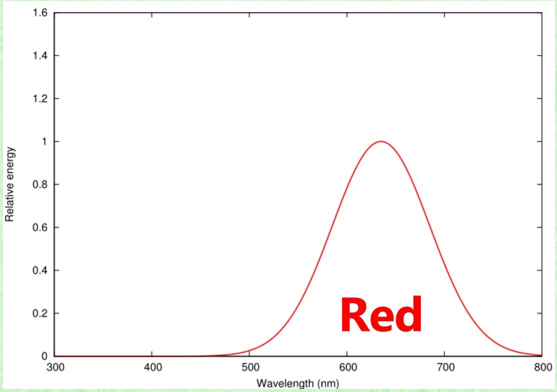


The human eye perceives combinations of light energy

Adding light energy refers to the process of combining multiple sources of light, or energy from light, to result in a total energy that is the sum of the individual contributions

Adding Light Energy

Energy is additive (per wavelength): $\boldsymbol{E(\lambda) = E_1(\lambda) + E_2(\lambda)}$



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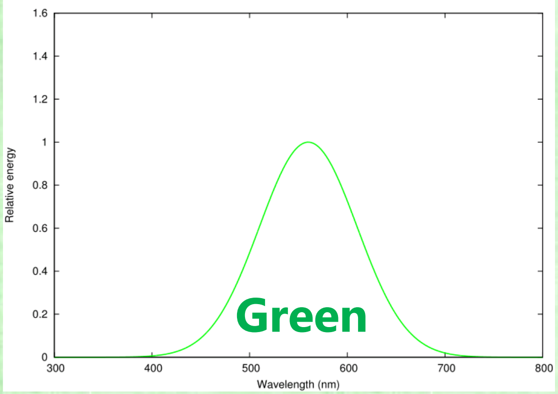

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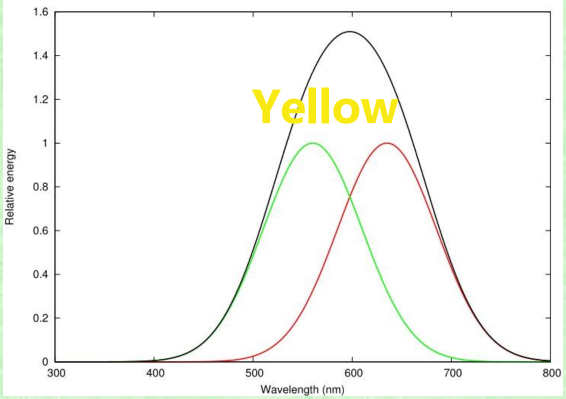

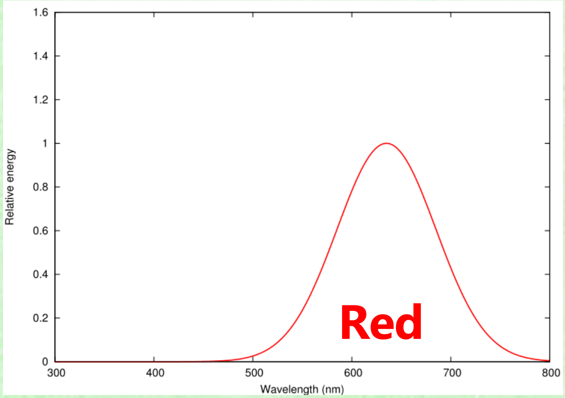

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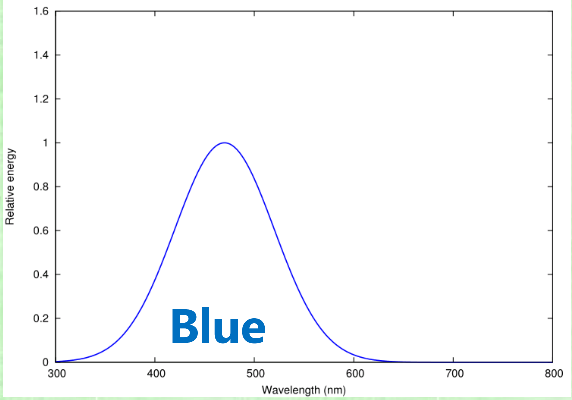

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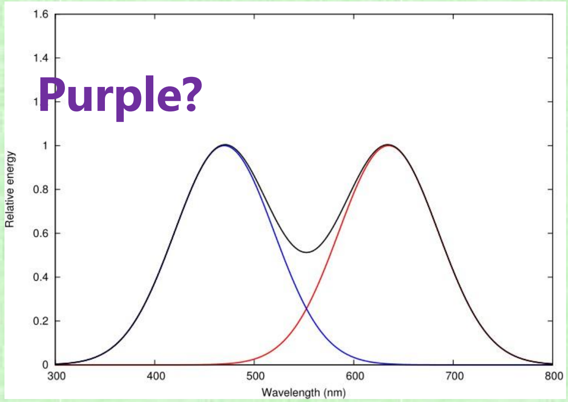
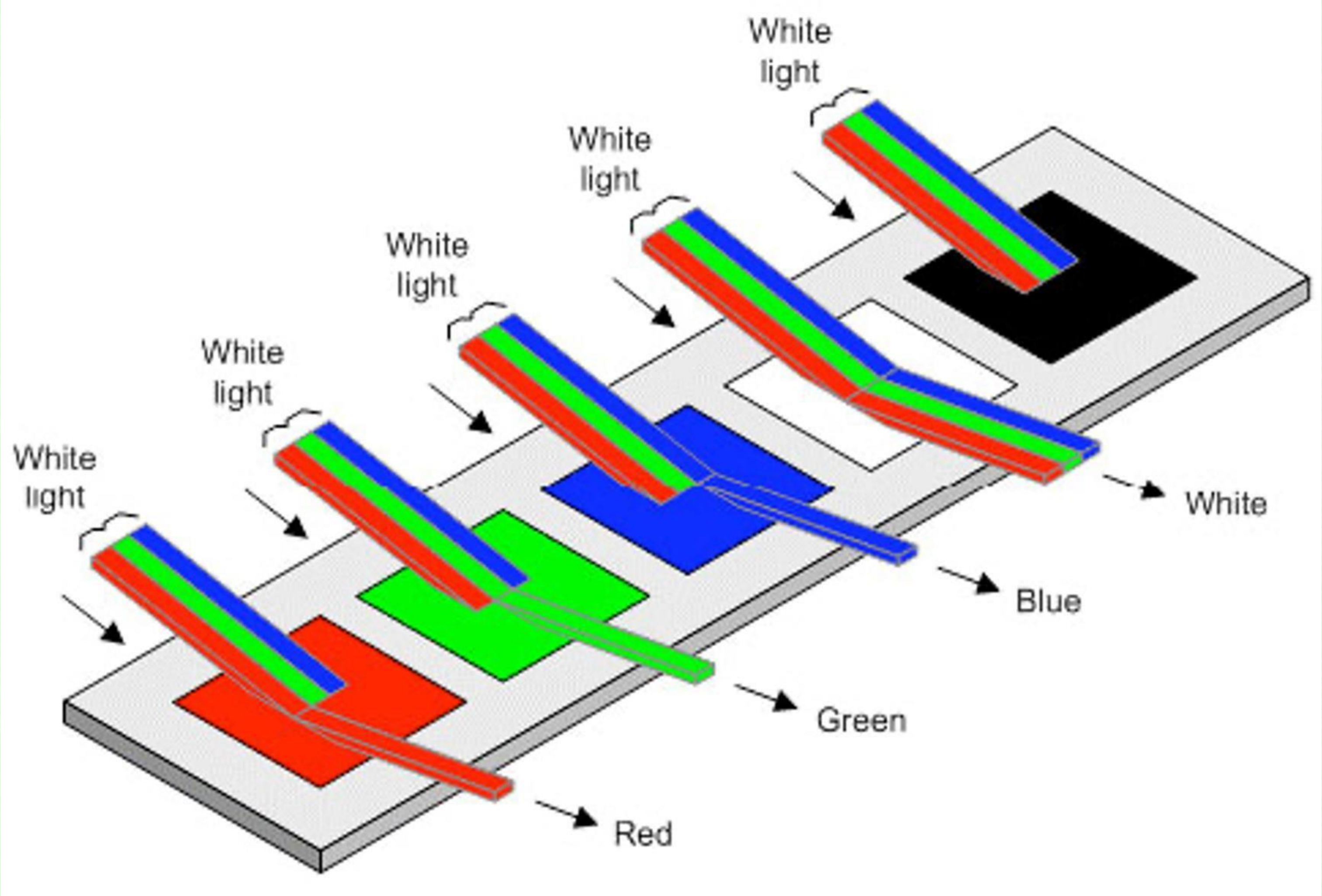


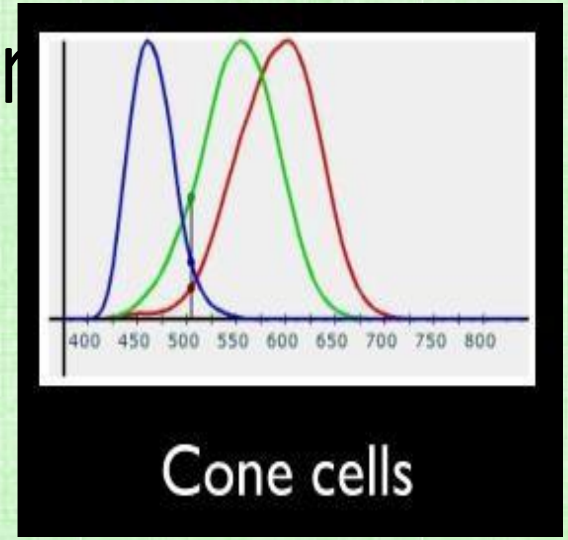
Absorbing & Reflecting Light Energy



Shining white light on different colored surfaces

Reflected light energy refers to the portion of the light energy that bounces off a surface when light strikes that surface, rather than being absorbed or transmitted through it

Absorbing & Reflecting Light Ener

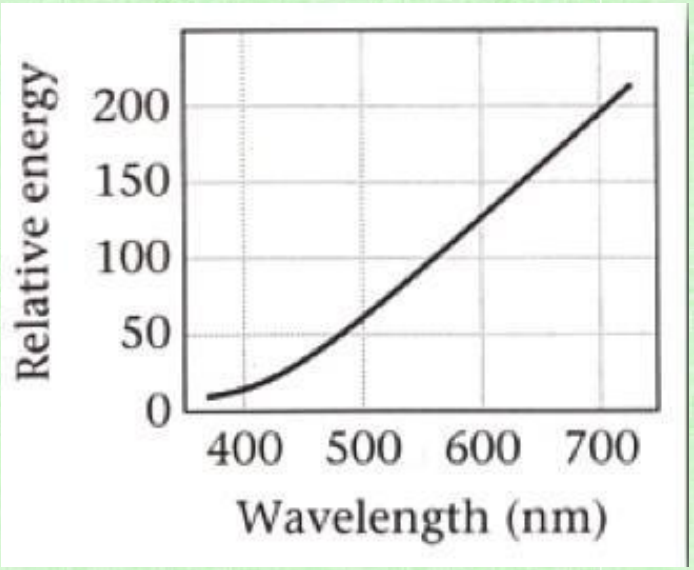


Light energy is either reflected or absorbed (per wavelength): $\mathbf{r}(\boldsymbol{\lambda}) + \boldsymbol{a}(\boldsymbol{\lambda}) = \mathbf{1}$

$$\mathbf{0} \leq \mathbf{r}(\boldsymbol{\lambda}), \boldsymbol{a}(\boldsymbol{\lambda}) \leq \mathbf{1}$$

Reflected light energy (per wavelength) is computed via:

$$\boldsymbol{Reflected}(\boldsymbol{\lambda}) = \boldsymbol{E}(\boldsymbol{\lambda})\boldsymbol{r}(\boldsymbol{\lambda}) = \boldsymbol{E}(\boldsymbol{\lambda})\big(\mathbf{1} - \boldsymbol{a}(\boldsymbol{\lambda})\big)$$



Incoming Energy

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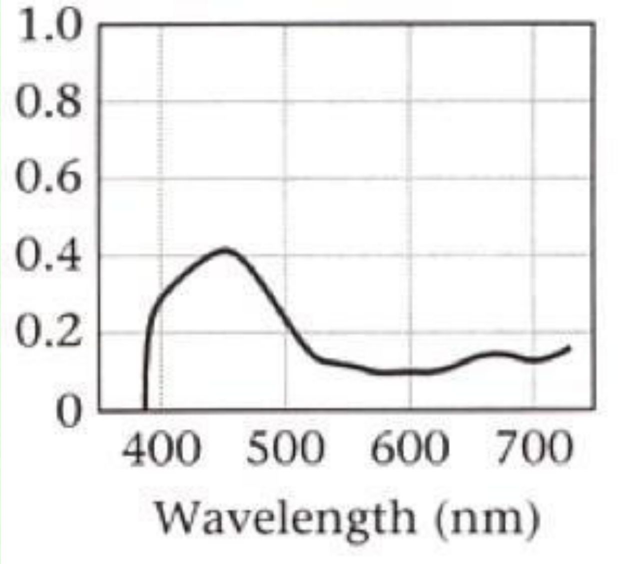

Surface Reflectance

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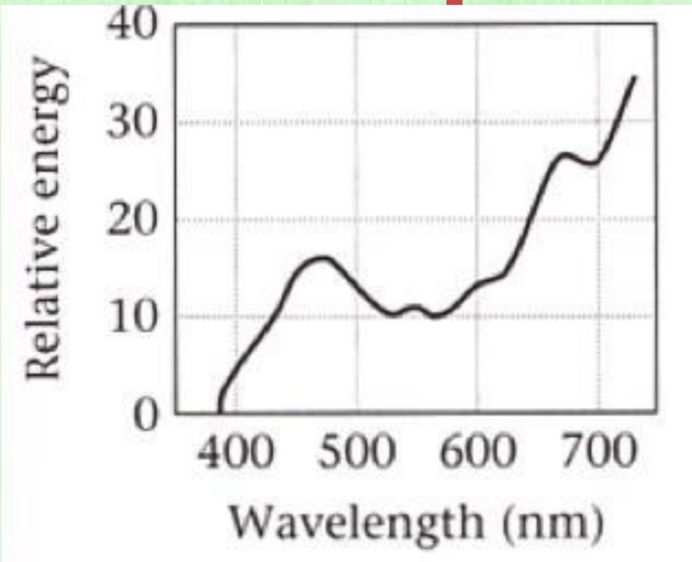


Reflected Energy

Let's consider the scenario where **red light** (with specific energy values) hits a **green surface**. The goal is to calculate how much of the **red light** gets absorbed by the green surface.

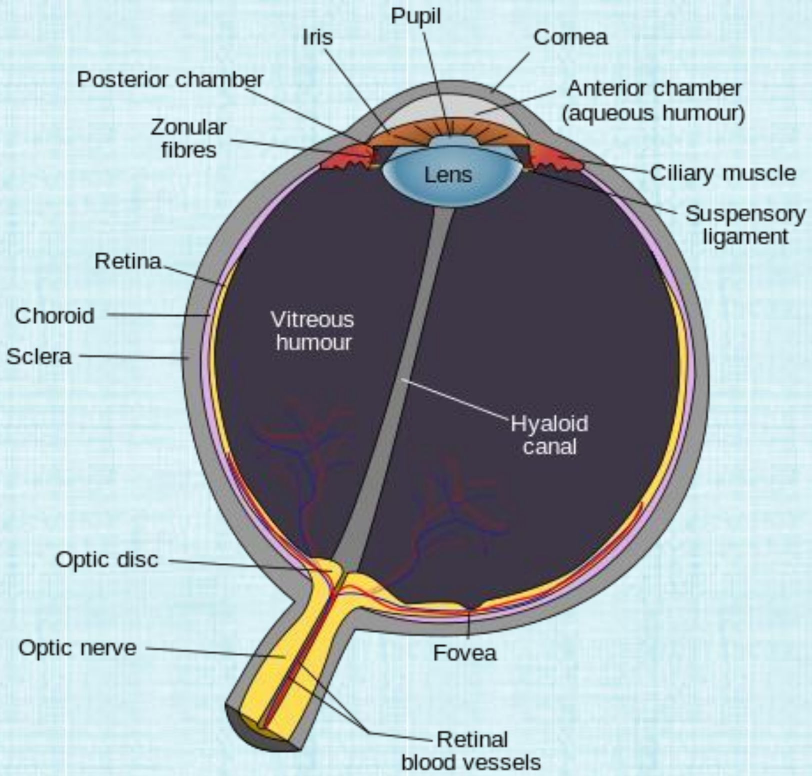
- The **total energy** of the red light at this wavelength is E (λ_{red}) =100 .
- The **green surface** reflects 30% of the red light at this wavelength: (λ_{red}) =0.30

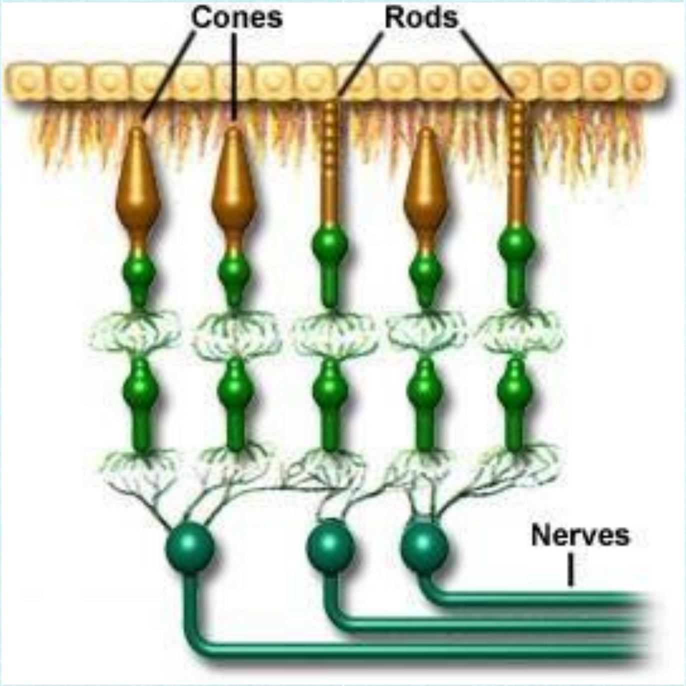
$$\mathbf{r}(\boldsymbol{\lambda}) + \boldsymbol{a}(\boldsymbol{\lambda}) = \mathbf{1}$$
$$\boldsymbol{a}(\boldsymbol{\lambda}) = \mathbf{1} - \mathbf{r}(\boldsymbol{\lambda})$$
$$\boldsymbol{a}(\boldsymbol{\lambda}) = \mathbf{1} - (30/100)$$
$$\boldsymbol{a}(\boldsymbol{\lambda}) = 0.70$$

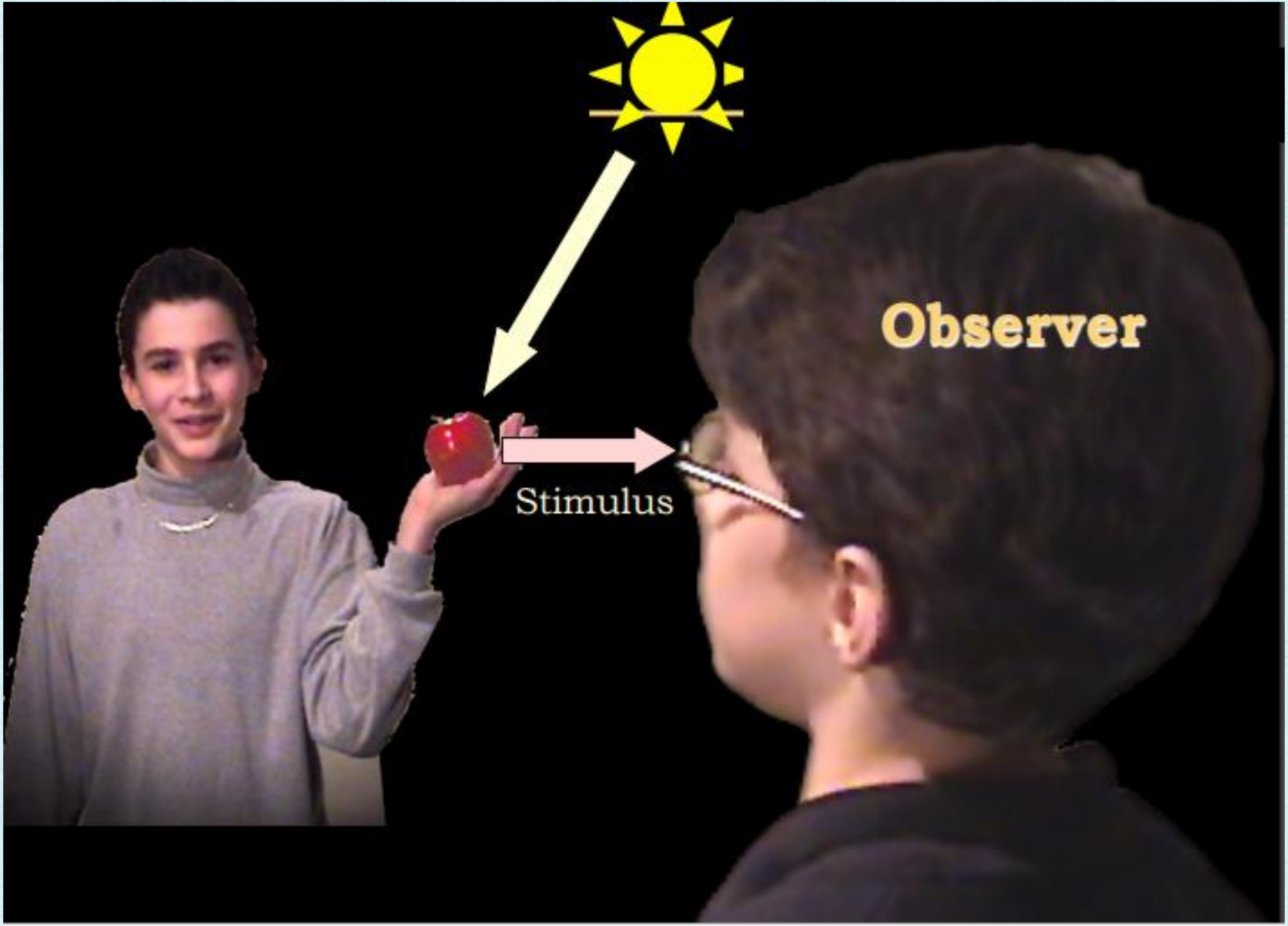
When red light with 100 J hits a green surface that reflects 30% of the light and absorbs 70%.

Sensors in the Human Eye

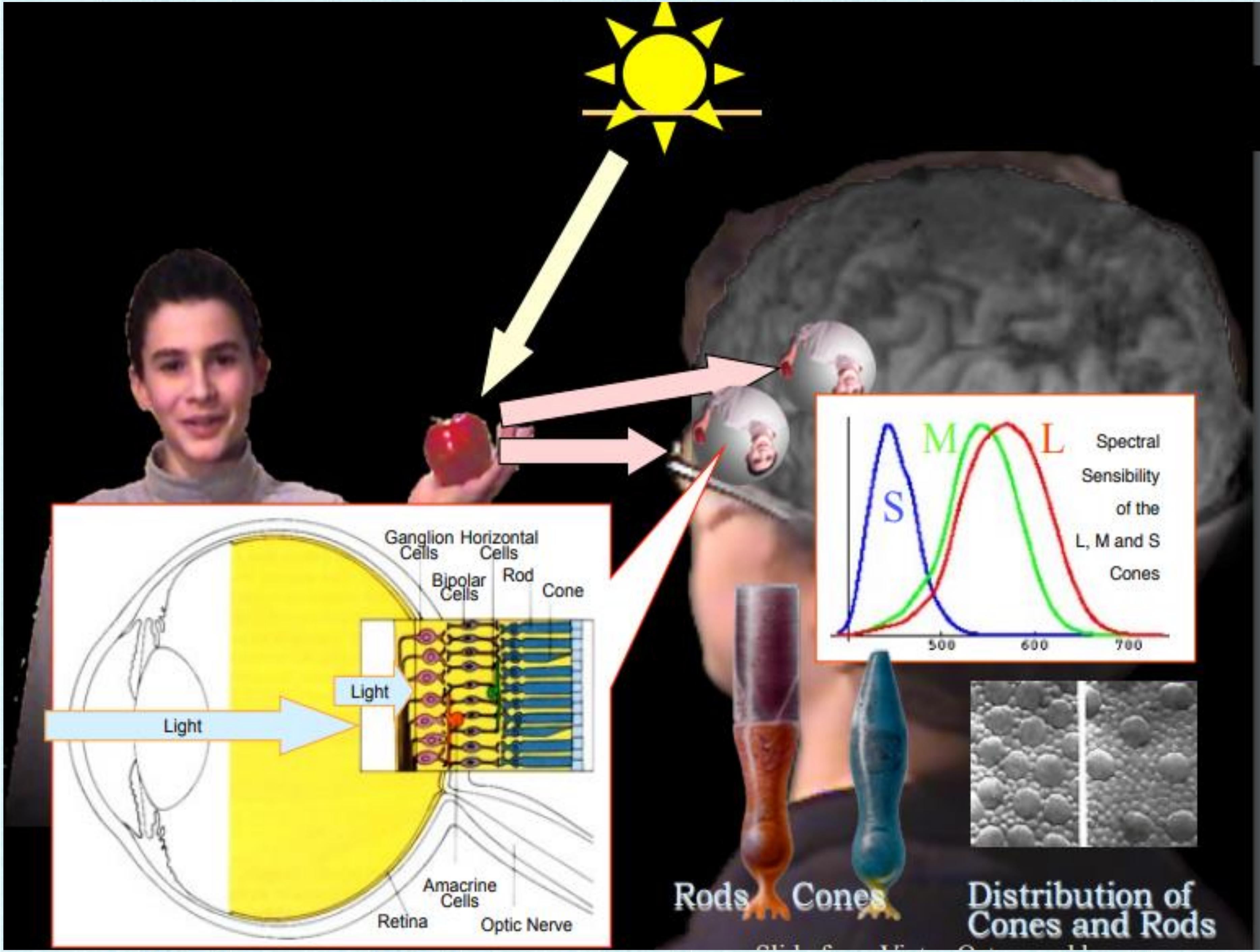
- The eye has 4 different kinds of sensors: 3 types of cone and 1 rod
- Proteins in the cone/rod cells absorb photons changing the cell membrane potential
- At night, cones are under-saturated (no/low/noisy signal), and rods produce most of the understandable signal
- During the day, the rod signals are over-saturated (maxed out), and we see primarily with cones





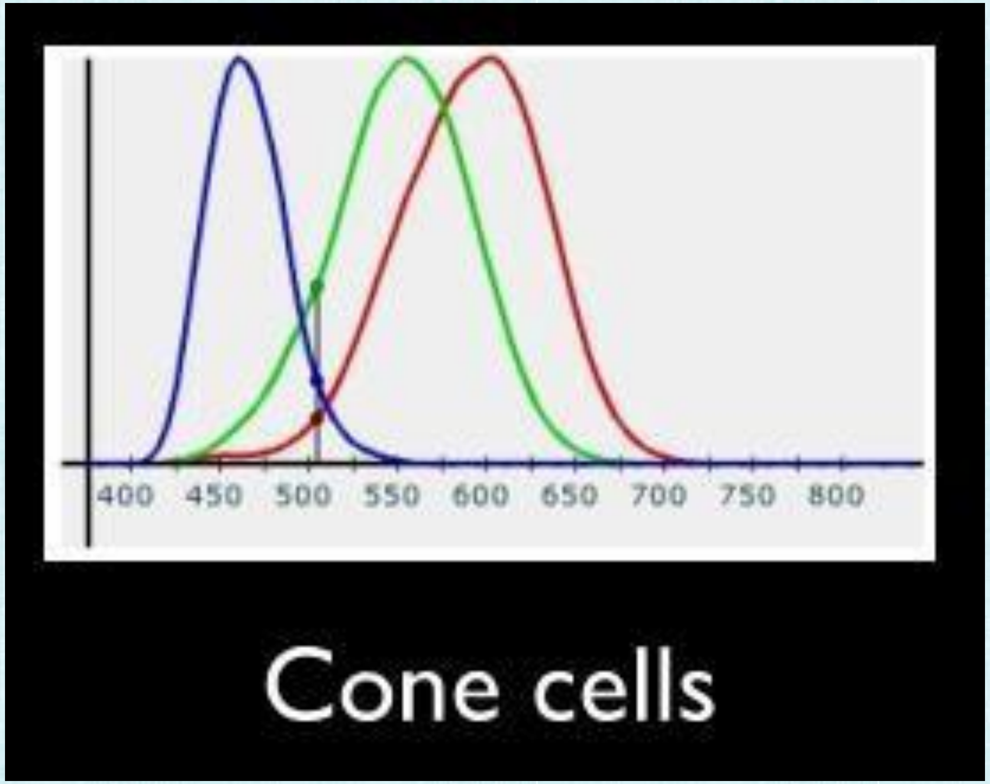

Observer
Stimulus

65% cones are sensitive to red, 33% are sensitive to green and the remining 2% are sensitive to blue lights, blue cones are most sensitive ones.

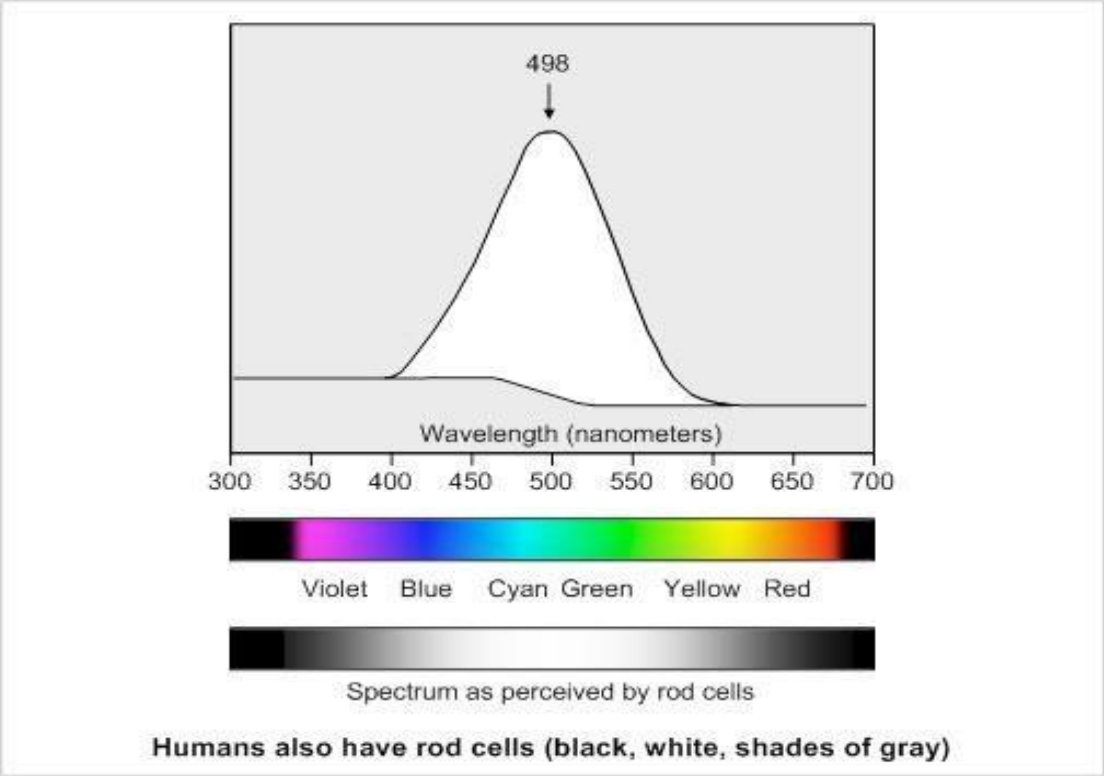


Response Functions for Cone/Rod Sensors

- The cone response functions vary based on the type of cone (red/green/blue cones)
- The rod sensor is interpreted as a gray-scale (from black to white) intensity



Note the similarity in red/green (regarding red/green colorblindness)



At night, the single signal from rods is interpreted as a shade of gray

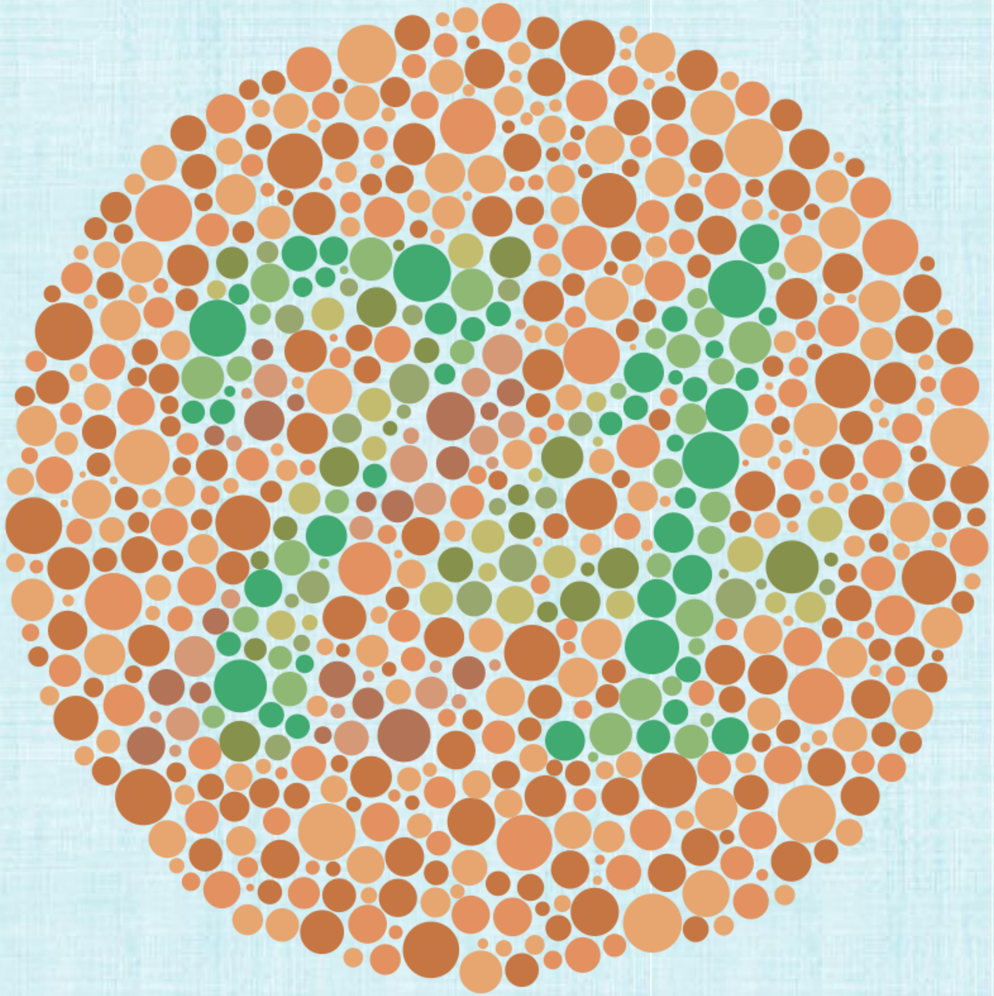
Trichromatic Theory

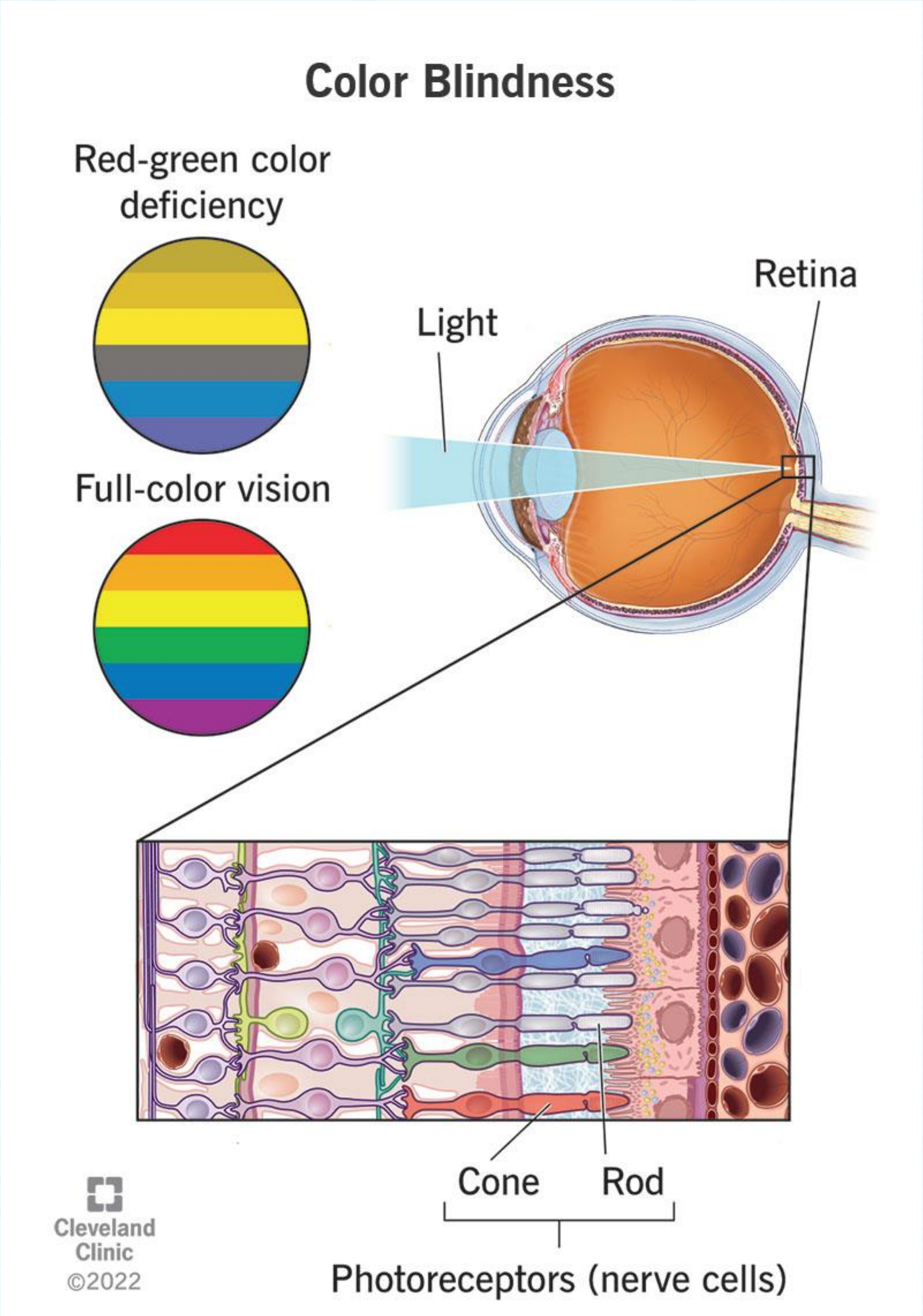
- Within your eye are tiny cells that can receive waves of light and translate them into one of three colors: blue, green and red.
- Given any human perceived "color" or any single wavelength of visible light:
  - Can adjust the brightness of 3 single wavelength lasers (e.g. R = 700 nm, G = 546 nm, B = 435 nm) to fool a human observer into "mistakenly" thinking that the laser combination exactly matches that "color"
  - This is doable because each of the three cones can only send one signal (i.e., a 3 dimensional basis)

"="

C "=" R "+" G "+" B

- Thus, only 3 signals are required for images, cameras, printers, displays, etc. (human perceived color is a 3 dimensional space!)
- Image formats store values in 3 channels: R, G, B




Color Blindness
Red-green color deficiency
Full-color vision
Light
Retina
Cone
Rod
Photoreceptors (nerve cells)
Cleveland Clinic
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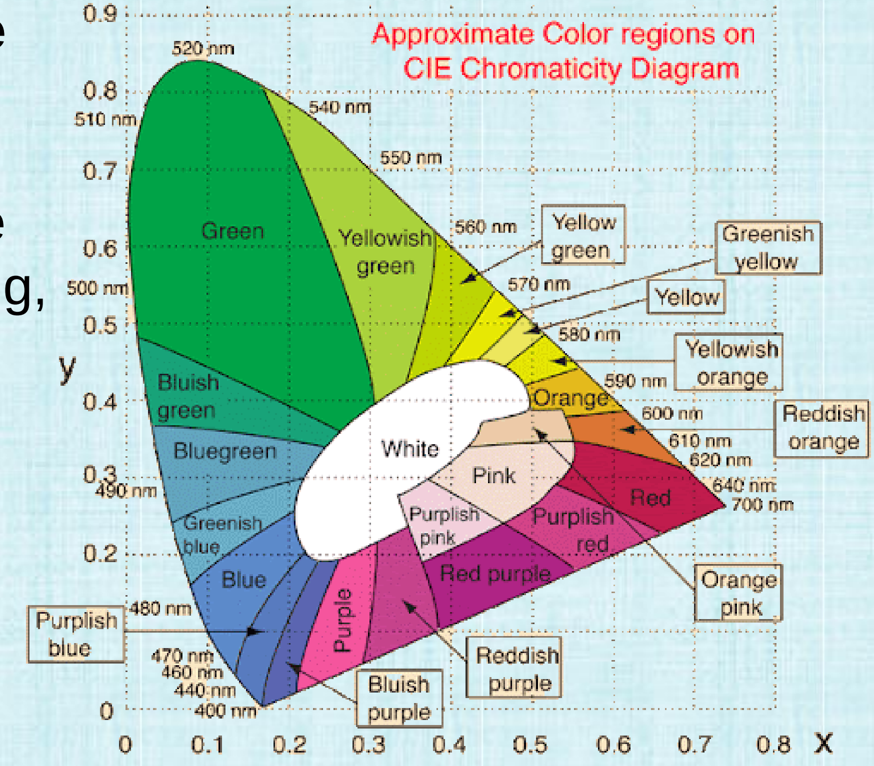
CIE

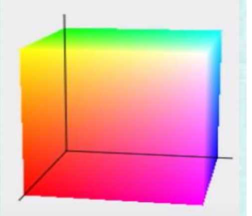
- CIE stands for the **Commission Internationale de l'Éclairage** (International Commission on Illumination). It is the **global authority on light, color, and vision** standards.
- The CIE develops **scientific models** for how humans perceive light and color, which are used in displays, photography, lighting, and color science.
- One of the first models to **quantify human color perception.**
- Defines how the **human eye perceives color** using three values:
  - **X (red-like response)**
  - **Y (green-like response, also represents brightness)**
  - **Z (blue-like response)**
- The CIE 1931 **chromaticity diagram** is widely used for defining colors in monitors, TVs, and cameras.



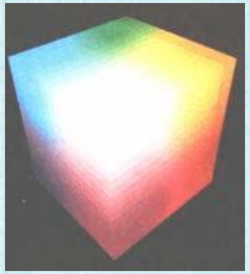
Difference Between CIE and Trichromatic Theory

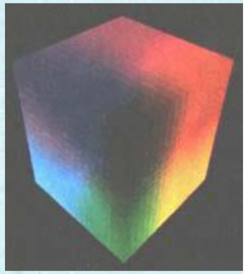
Feature	Trichromatic Theory	CIE (International Commission on Illumination)
Focus	Explains how the human eye perceives color using three types of cones.	Provides standardized color models for scientific and industrial use.
Origin	Proposed by **Young-Helmholtz** in the 19th century.	Established in **1931** to define color mathematically.
How it Works	The eye detects color through **three cone types** (S, M, L cones for blue, green, and red).	Defines colors using **CIE XYZ, Lab, and LUV color spaces** for precise color measurement.
Purpose	A biological theory explaining how the **eye** sees color.	A mathematical framework to **quantify color for displays, printing, and lighting**.
Use Cases	Explains **color blindness and human vision**.	Used in **display calibration, photography, and color science**.

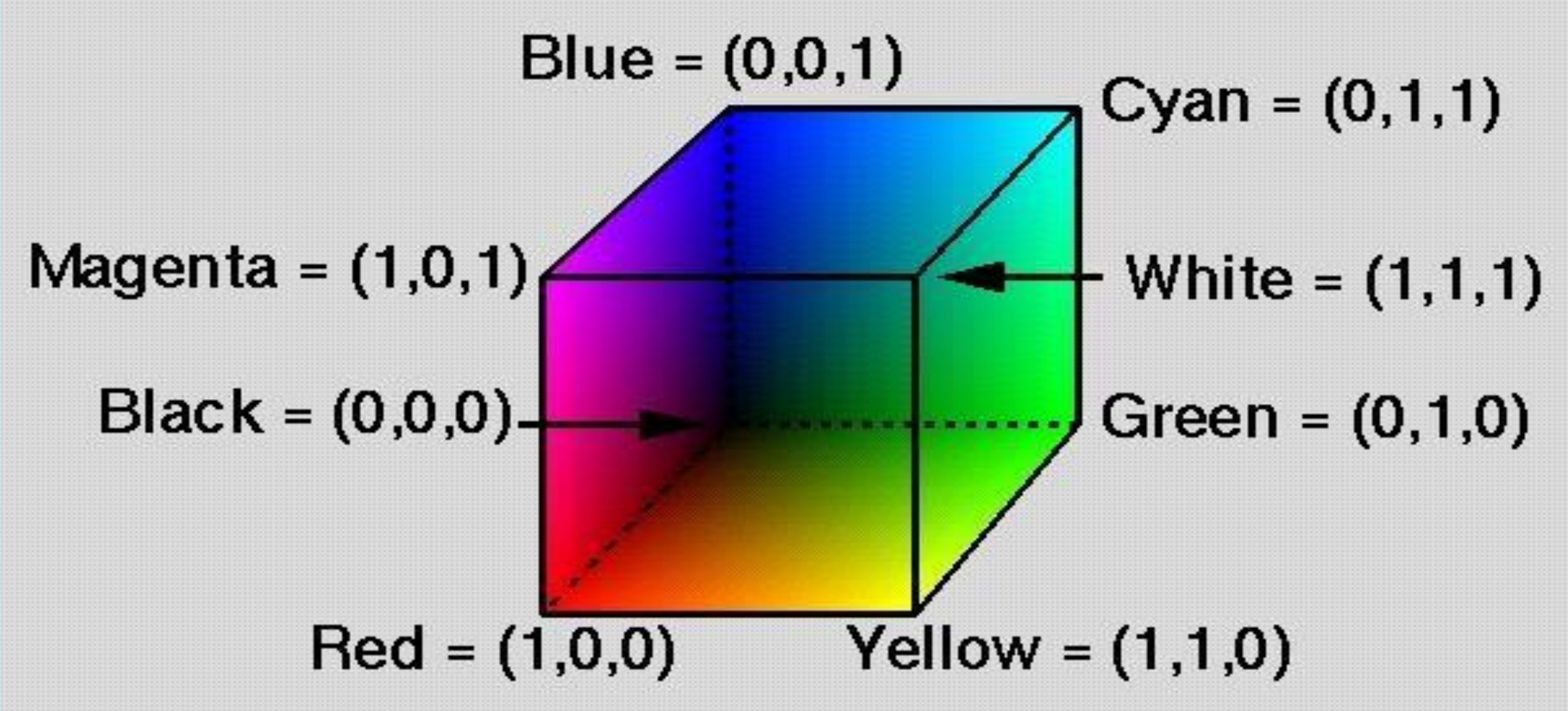
3D Color Space (RGB)



- Map each primary color (Red, Green, Blue) to the unit distance along the x, y, z axes
- Black at (0,0,0), white at (1,1,1)
- The resulting RGB Color Cube represents all possible colors







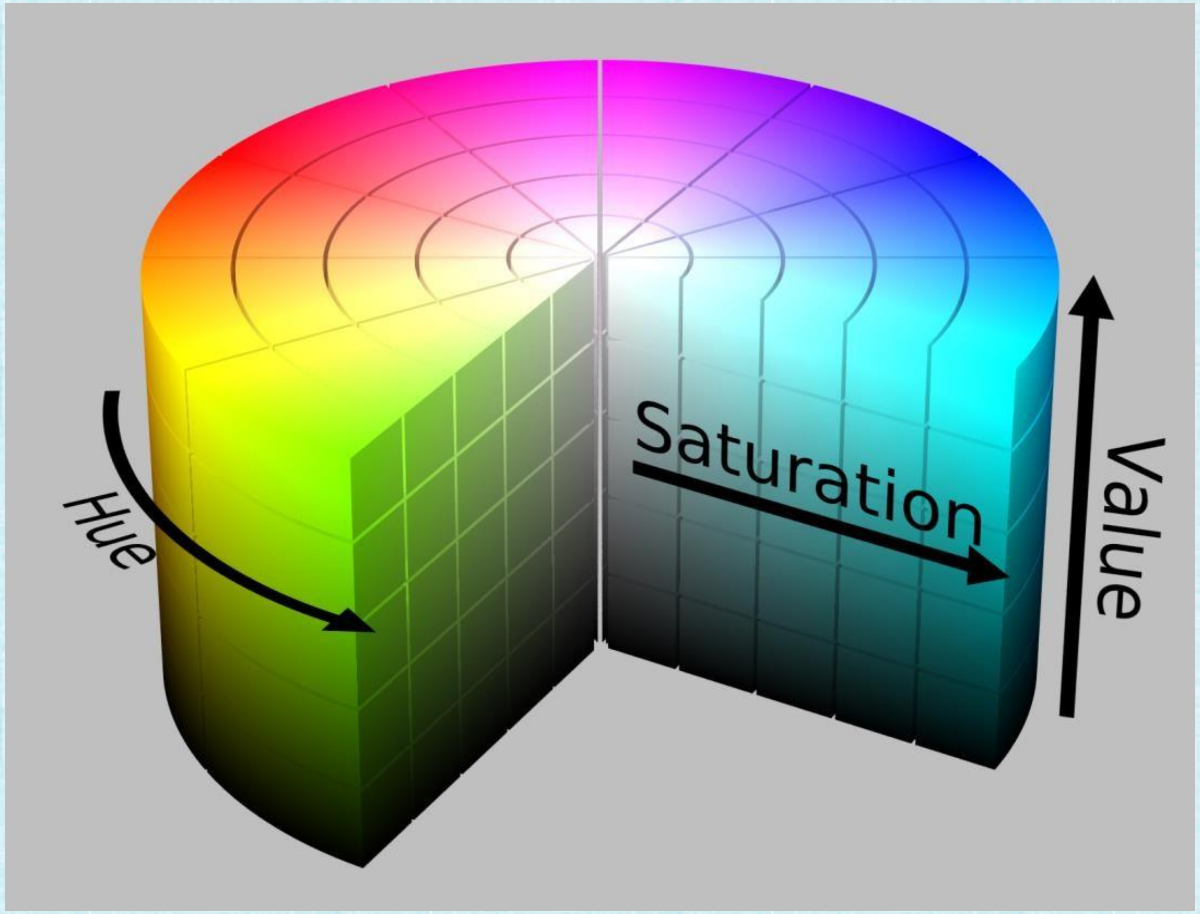
3D Color Space (Cylindrical HSV Color Space)

- A better 3D color space for <u>user interfaces</u> is based on Hue, Saturation, and Value (HSV)
- <u>Hue:</u> rainbow of colors (“wavelength”)
- <u>Saturation:</u> intensity for a particular color
- <u>Value:</u> lightness or darkness of a particular color

•**Hue** is represented as the angle around the vertical axis of the cylinder.

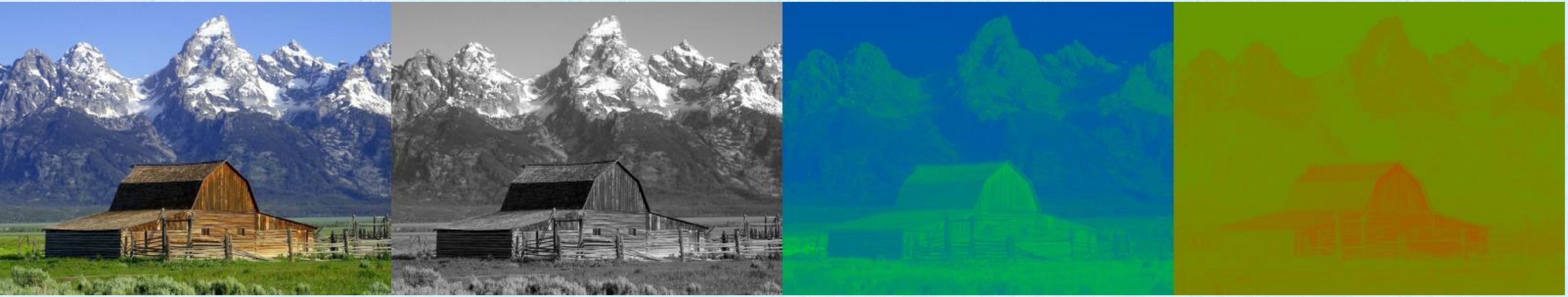
•**Saturation** is the distance from the centre of the cylinder.

•**Value** is the height along the cylinder's vertical axis.



3D Color Space (Luminance and Chrominance (YUV))

- Another 3D color space: uses 1 luminance (Y) and 2 chrominance (UV) channels
- Black and White televisions use Y only, which perceptually holds the most spatial details
- Thus, can compress more aggressively in U & V than in Y

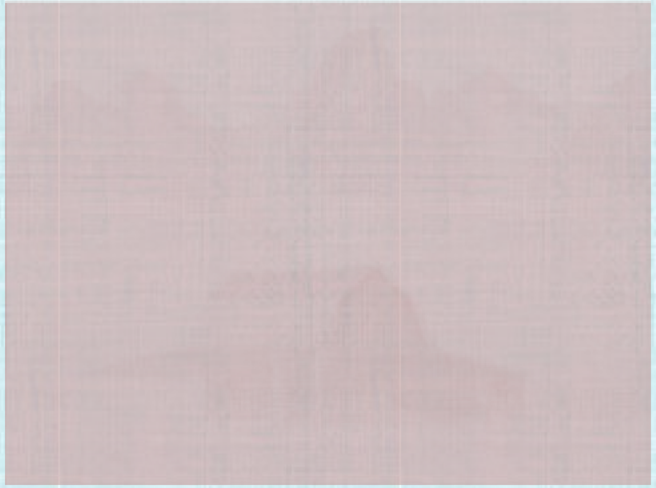


Original Y U V









Interchangeability of 3D Color Spaces

- Can map back and forth between 3D color spaces via matrix multiplication (using an appropriate matrix and its inverse)

- For example:

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

$$\begin{bmatrix} R \\ G \\ B \end{bmatrix} = \begin{bmatrix} 1 & 0 & 1.13983 \\ 1 & -0.39465 & -0.58060 \\ 1 & 2.03211 & 0 \end{bmatrix} \cdot \begin{bmatrix} Y \\ U \\ V \end{bmatrix}$$

- Aside: note how important the Green channel is for the details in Y, as well as how unimportant the Blue channel is for those detail

Additive color and Subtractive color models

- Additive color is color created by mixing light of two or more different colors.
- Red, green, and blue are the additive primary colors normally used in additive color system.
- Since additive color models display color as a result of light being transmitted, the total absence of light would be perceived as black.

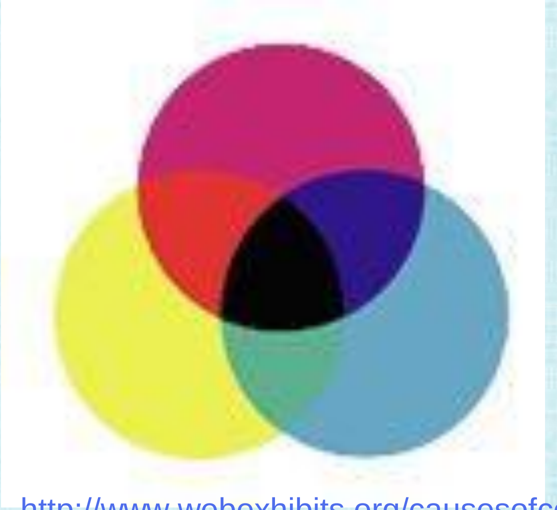
Additive color and Subtractive color models

- A subtractive color model explains the mixing of a limited set of dyes, inks, paint pigments or natural colors to create a wider range of colors.

- Subtractive color models display color as a result of light being absorbed (subtracted) by the printing inks.

Color Addition and Subtraction

Primary Colors of Light: Red, Green, Blue



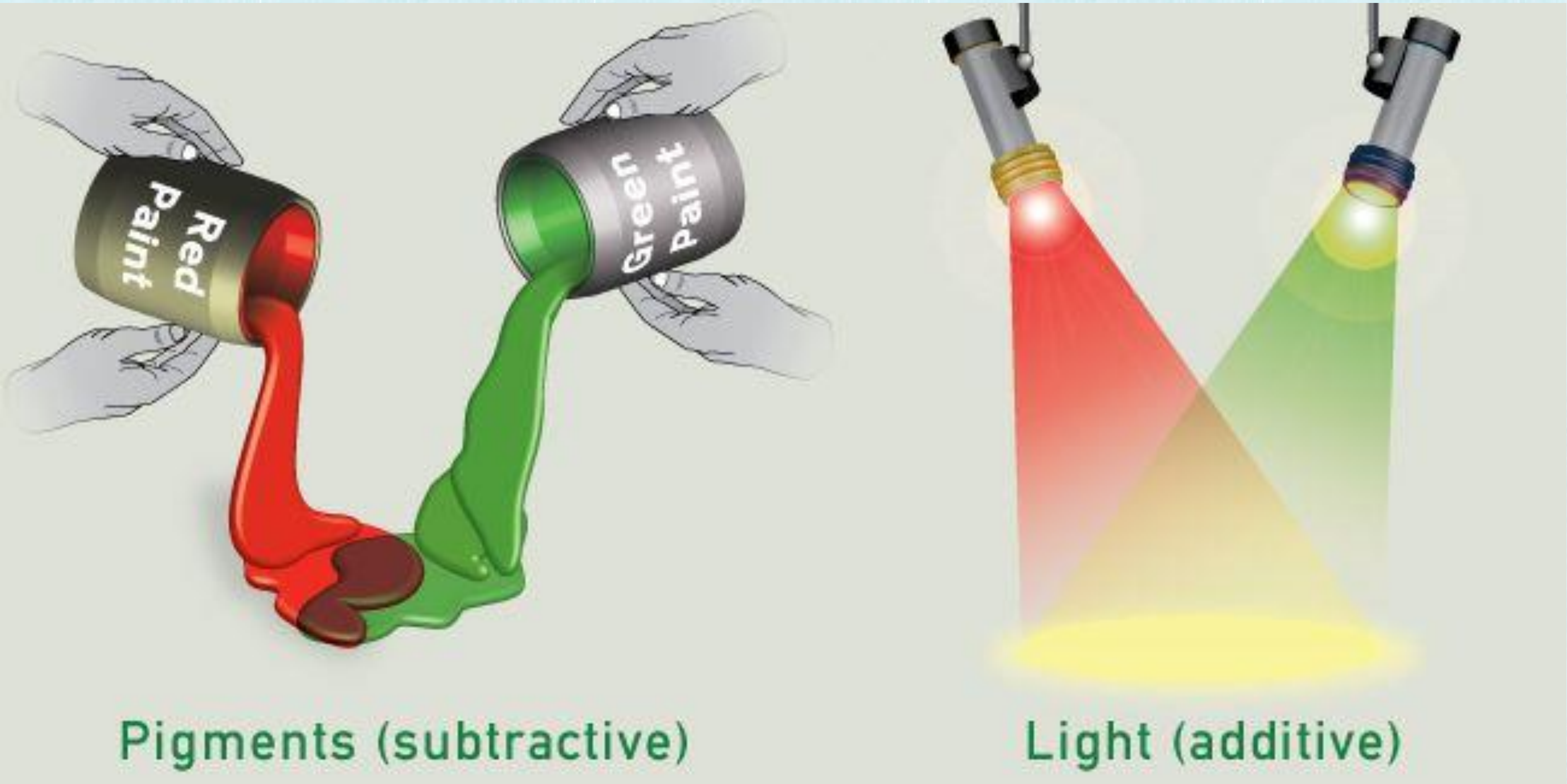
http://www.webexhibits.org/causesofcolor/1BA.html

Adding light colors generate new colors on the color wheel and becomes lighter as more color is added.

Additive mixing of colors is what is operational in any colored display device (TV, computer monitor)

Subtracting red, green and blue from white light gives you cyan, magenta and yellow. Mixing these colors gives you the colors on the color wheel. As you add more and more of cyan, magenta and yellow, the mixture turns darker towards black. This is operational in paints, pigments and printing.

Mixing pigments and mixing light have very different color outcomes


Red Paint
Green Paint
Pigments (subtractive)
Light (additive)

Printers (CMYK)

- Printers use subtractive color spaces
- Ink partially or entirely masks/filters/absorbs colors on a white background, reducing the light that would otherwise be reflected

- Cyan, Magenta, Yellow (CMY) are the three primary colors of the subtractive color model

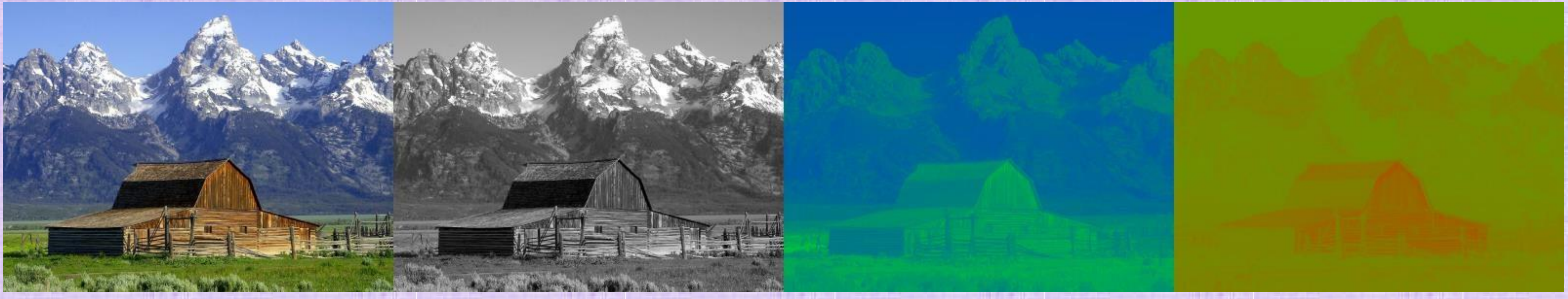
- Equal mixtures of C, M, Y (ideally) produce all shades of gray
- However, in practice, ink mixtures do not give perfect grays
- In addition, it’s difficult to get perfect alignment of the 3 inks

- Thus, most fine details are printed with the Key color (= K = black)
- This also reduces ink bleeding, reduces the time for ink to dry, and saves money on colored ink

C
M
Y
K

Brightness (Luminance)

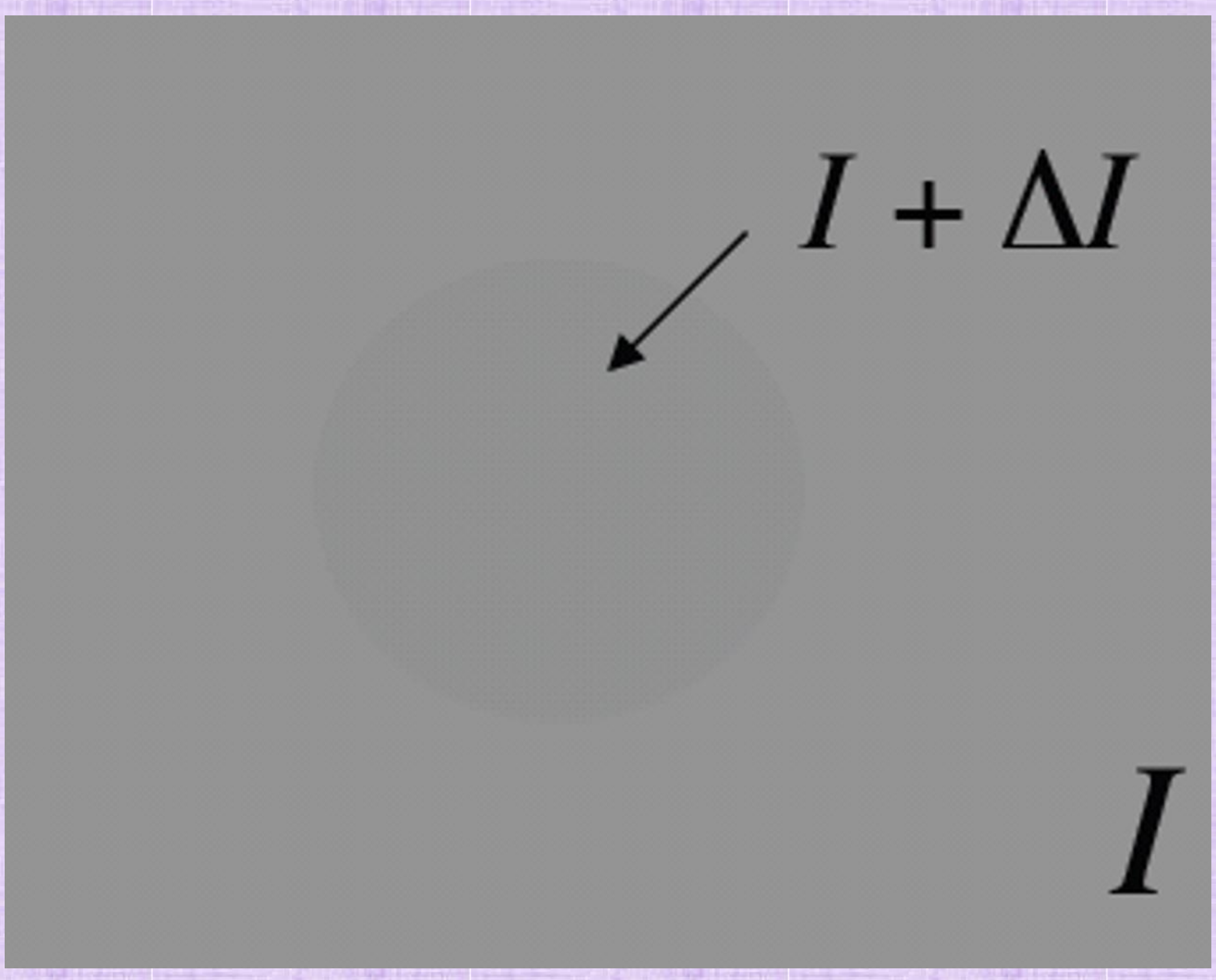
- The human eye is more sensitive to <u>spatial variations</u> in brightness (gray-scale) than to spatial variations in color
- The 3 images on the right add together to give the image on the left
- Notice which image on the right has the most spatial details



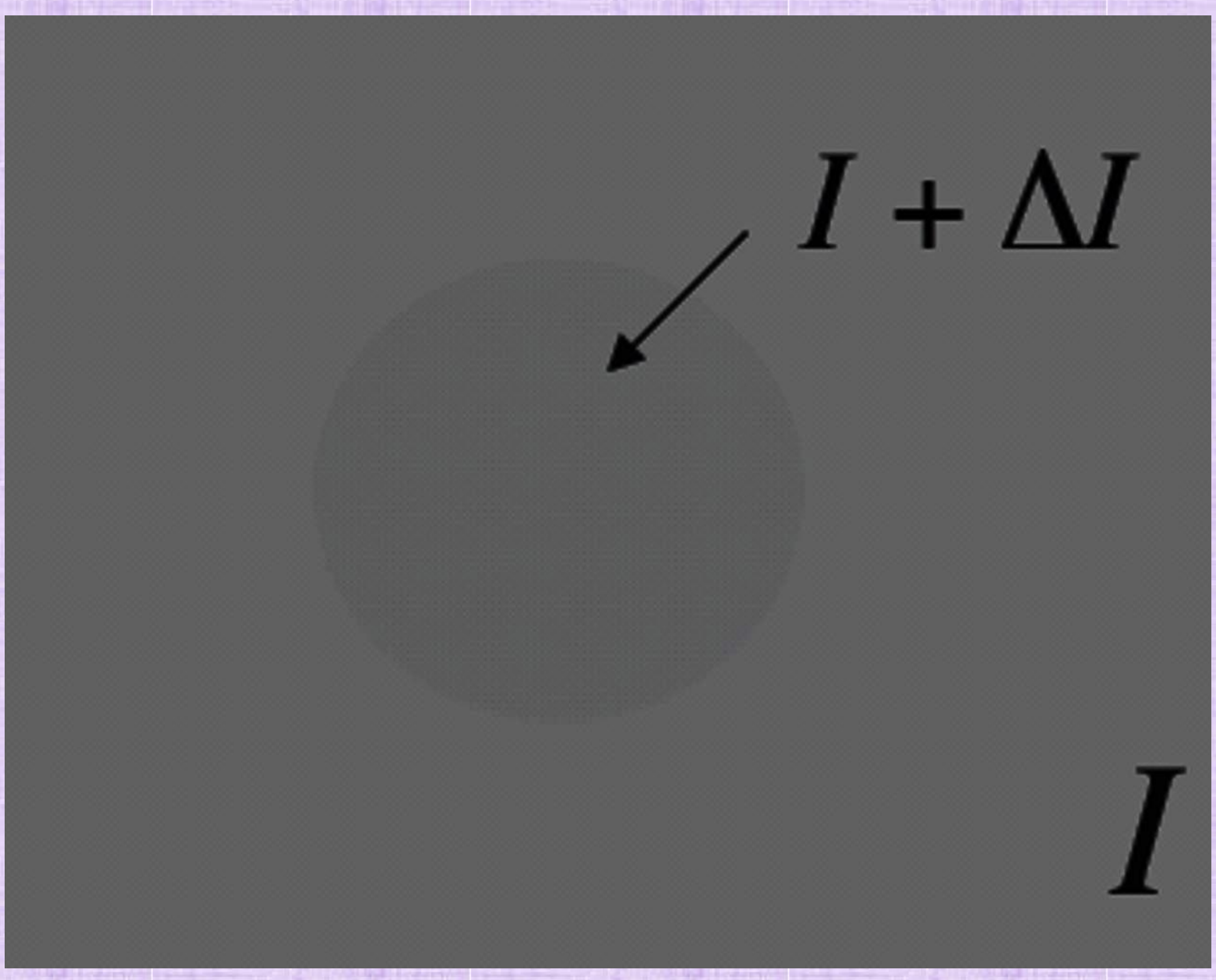
original image = gray-scale + color 1 + color 2

Brightness Discrimination Experiment

- Changing the brightness (intensity) of the circle by 1 to 2% makes it just noticeable to most observers

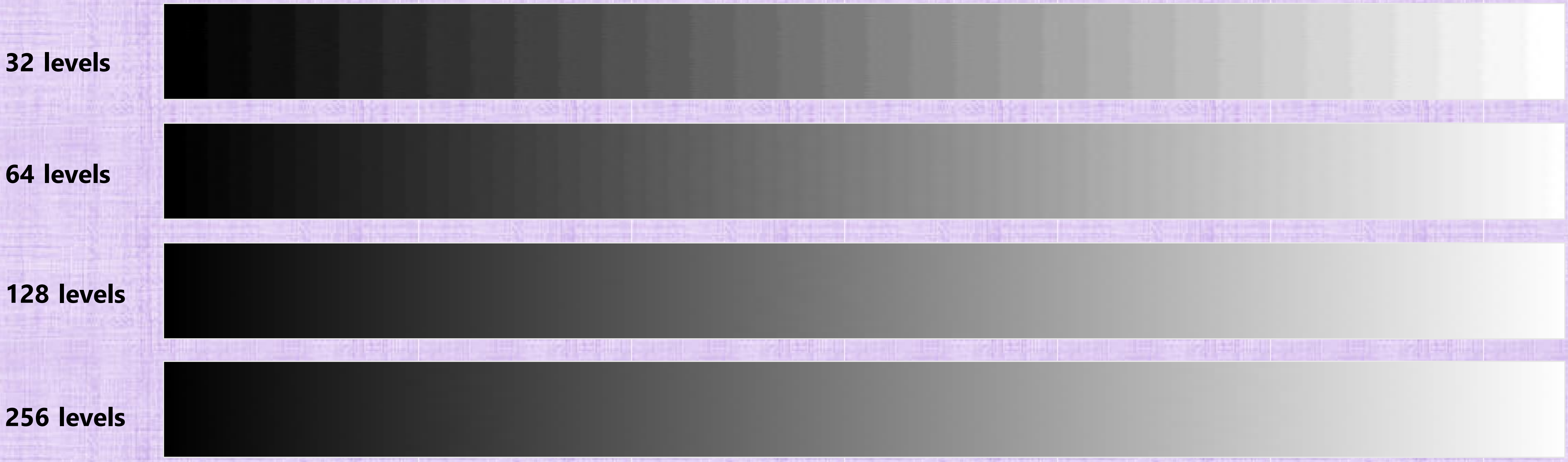


Brightness Discrimination Experiment



Discretizing Brightness

- Since our eye can see small changes in brightness, we need many levels for brightness
- Otherwise, changing brightness by the smallest amount looks discontinuous
- We typically use 256 levels for brightness; that is, we store each color channel (R, G, B) with an integer ranging from 0 to 255
- High Dynamic Range (HDR) image formats use an even larger range than 0-255



Dynamic Range

- 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
    - <u>Static contrast ratio:</u> luminance ratio between the brightest white and darkest black in a *single* image
    - <u>Dynamic contrast ratio:</u> luminance ratio between brightest white possible (on any image) and the darkest black possible (on any image) on the same device
  - A monitor's contrast ratio is measured in a dark room.
  - The effective contrast ratio typically drops from 3,000:1 to less than 200:1 in normal office lighting conditions.

Dynamic Range (an example)

- 16 photographs of the Stanford Church (half as much light hits the film in each successive picture)
- No image captures everything desirable in both the darkest and the brightest regions (some pixels are over-saturated and others have no signal at all)

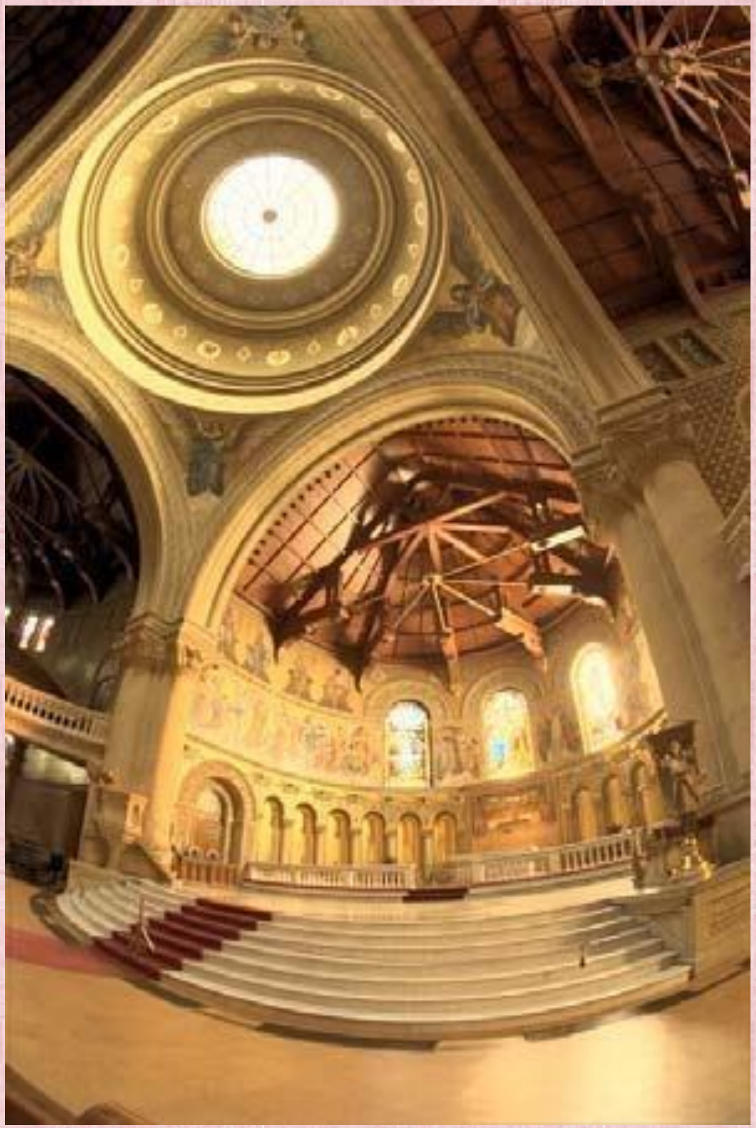
From Debevec and Malik, High Dynamic Range Photographs

Tone Mapping

- "Compositing" all the information from all the images gives a result with a High Dynamic Range (i.e., 0-X with X >> 255)
- That range is too large for the standard image format (since X > 255)
- Solution #1: Linearly rescale/compress the values so that X=255
  - Small intensity differences are quantized (a range of values map to the same integer), and relative differences (and thus details) are lost.
    - If an HDR image has brightness values ranging from 0 to 10,000, compressing it linearly to 0-255 means many fine details in bright areas (e.g., clouds in the sky) and dark areas (e.g., shadows) are lost.
- Solution #2: Use a logarithmic map to rescale/compress
  - Information is still quantized, but in a way that exploits human "perceptual space".
  - It **compresses large brightness values more than small ones** using a logarithm.
    - In a night scene with a bright moon, logarithmic mapping **keeps both the dark sky and bright moon visible**, whereas linear scaling might make the sky completely black or the moon a white blob
- Solution #3: Other approaches…
  - E.g., Local operators: map each pixel value based on surrounding pixel values (human vision is sensitive to *local* contrast)

Linear vs. Logarithmic Compression

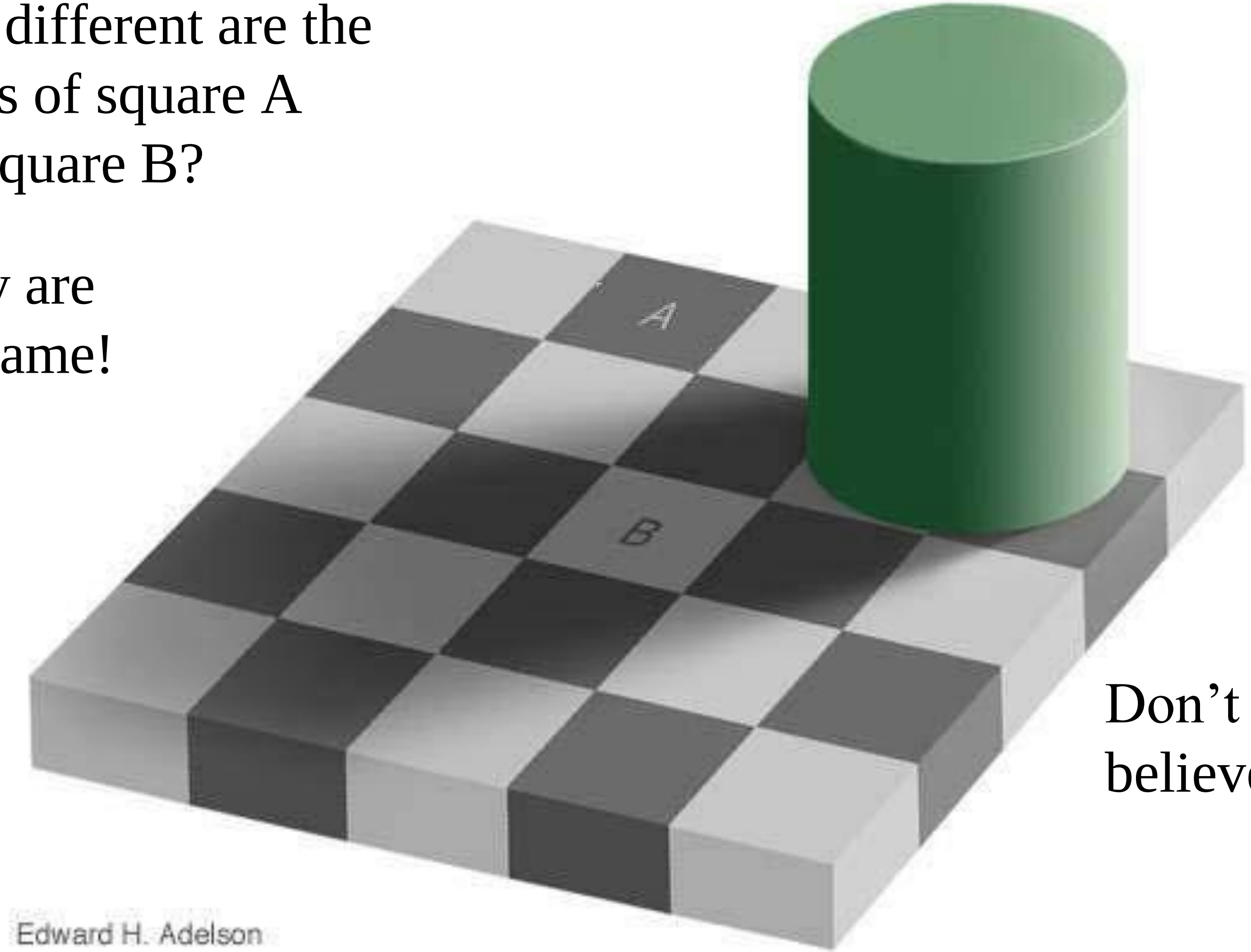
Linear



Logarithmic

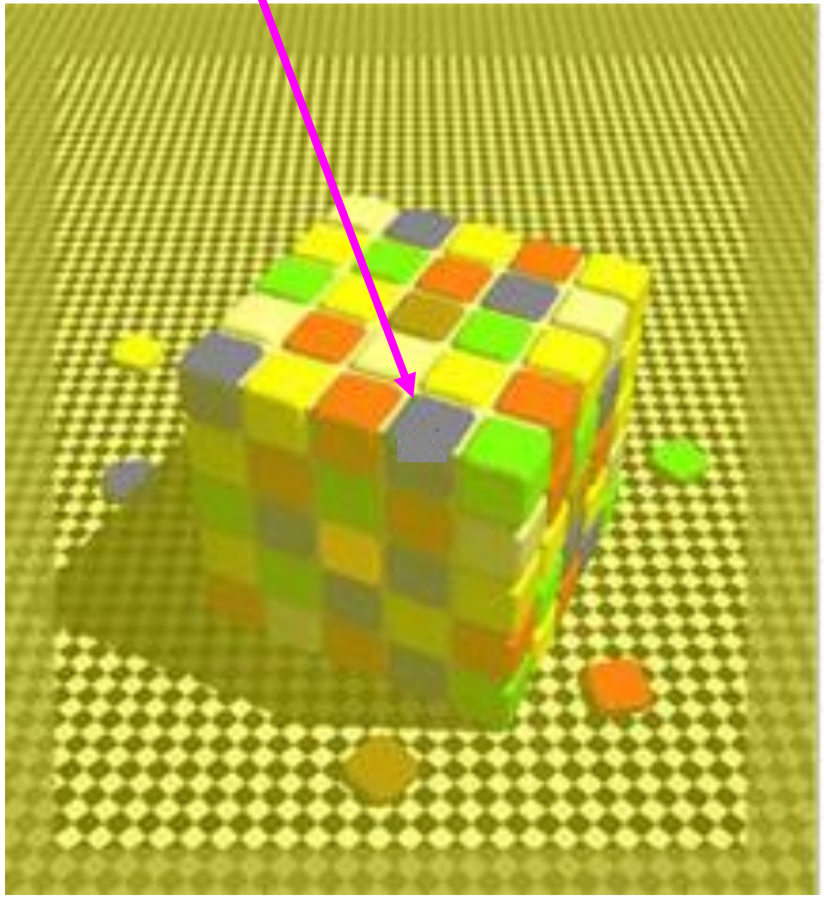
How different are the colors of square A and square B?

They are the same!

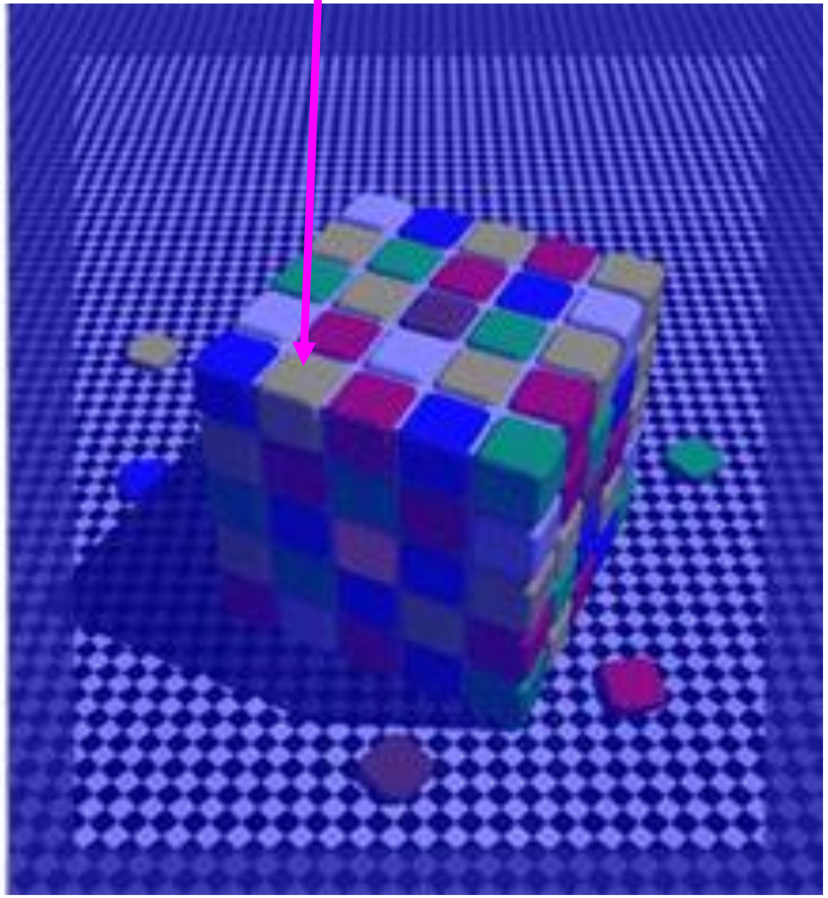


Don’t believe me?

What color is this blue cube?

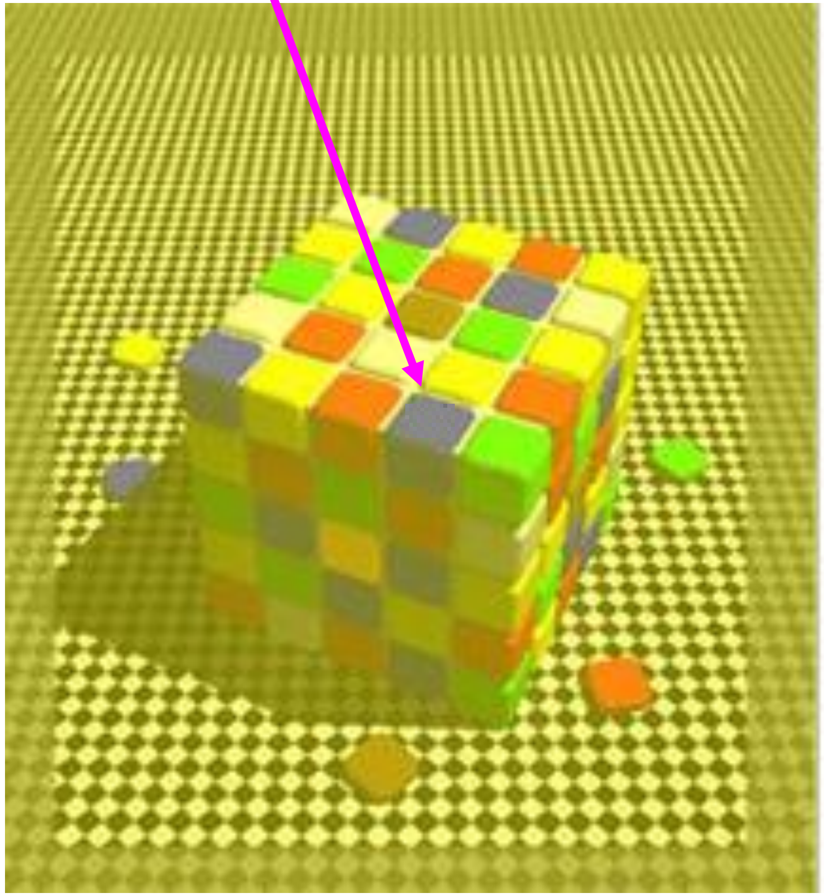


How about this yellow cube?

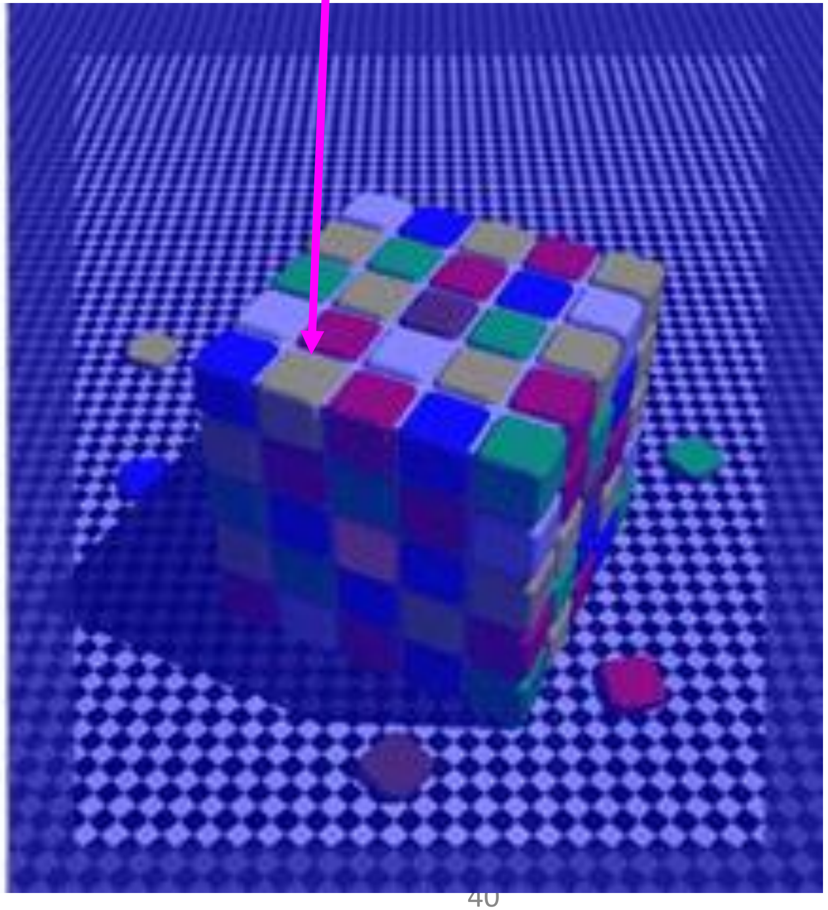


Want to see it slower?

What color is this blue cube?



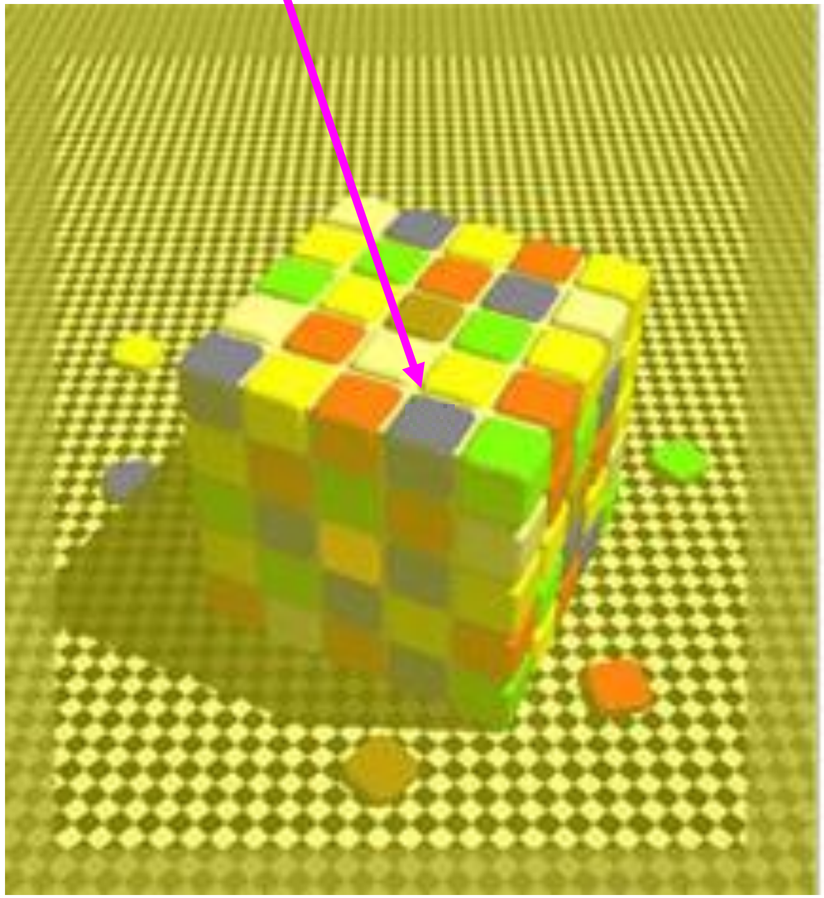
How about this yellow cube?

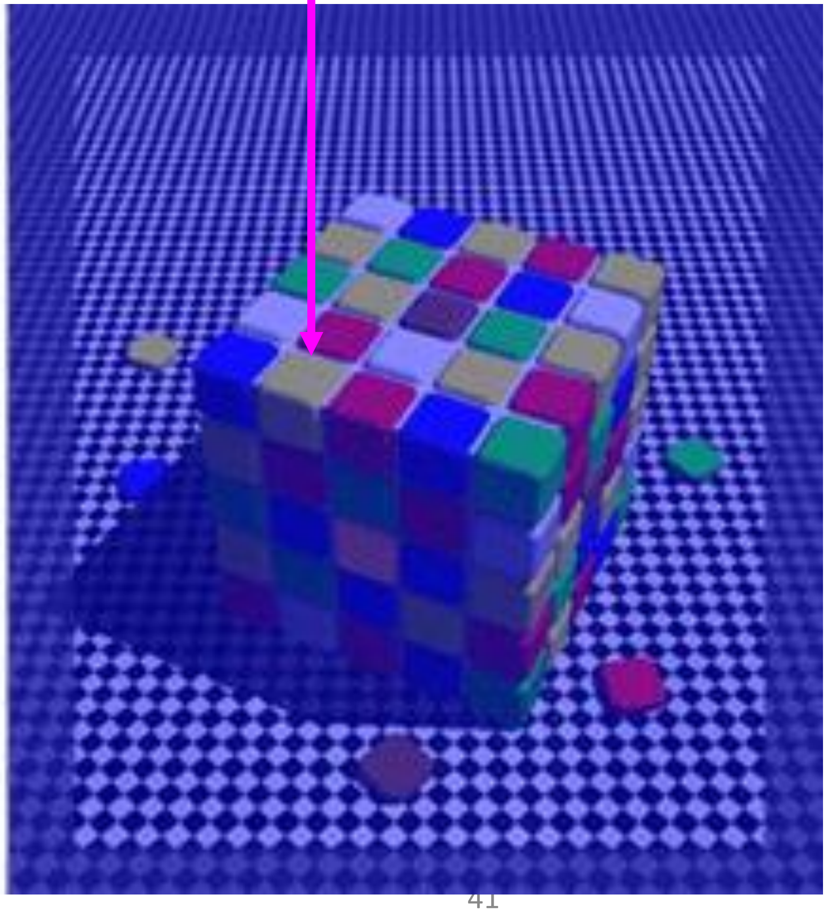


Even slower?

What color is this blue cube?

How about this yellow cube?





So what color is it?

What color is this blue cube?

It's gray!

How about this yellow cube?