# Color and Light

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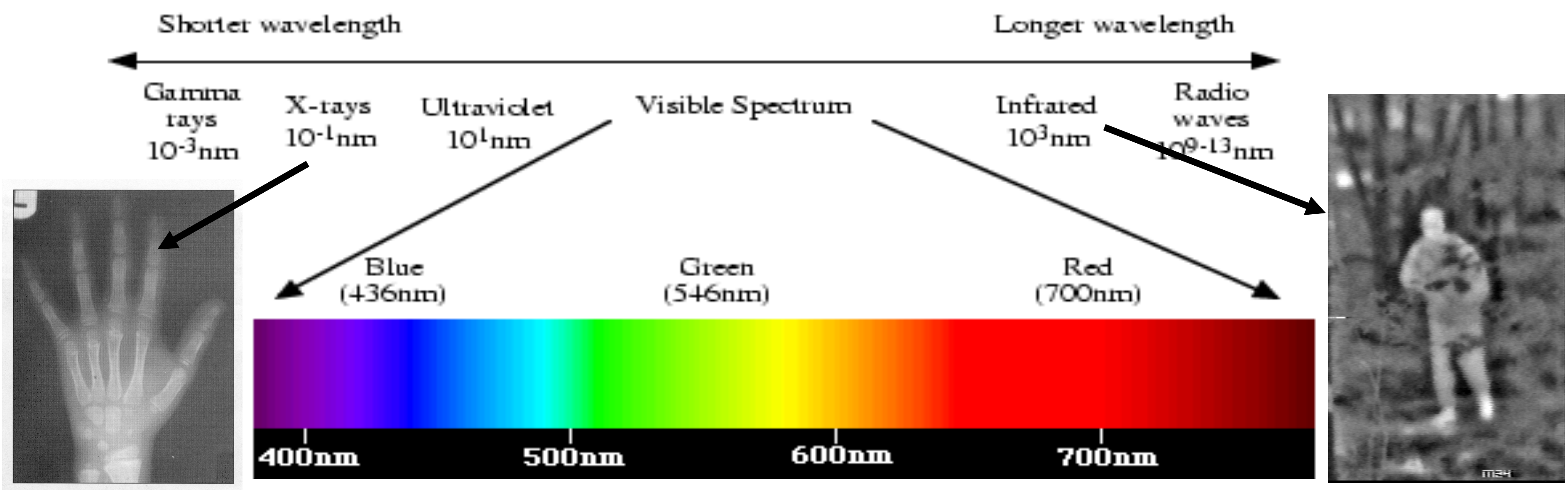
# Physics of Light and Color

- Light is electromagnetic radiation
  - Different colors correspond to different ***wavelengths*** $\lambda$
  - Intensity of each wavelength specified by ***amplitude***
- Visible light: 400-700nm. range




V I B G Y O R

(ROYGBIV)

# What is Color?

- Objects don’t have a “color”
- Color is a perception; what we “see”
- It is a function of
  - light source power at different wavelengths
  - proportion of light at each wavelength reflected off object surface
  - sensor response to different wavelengths

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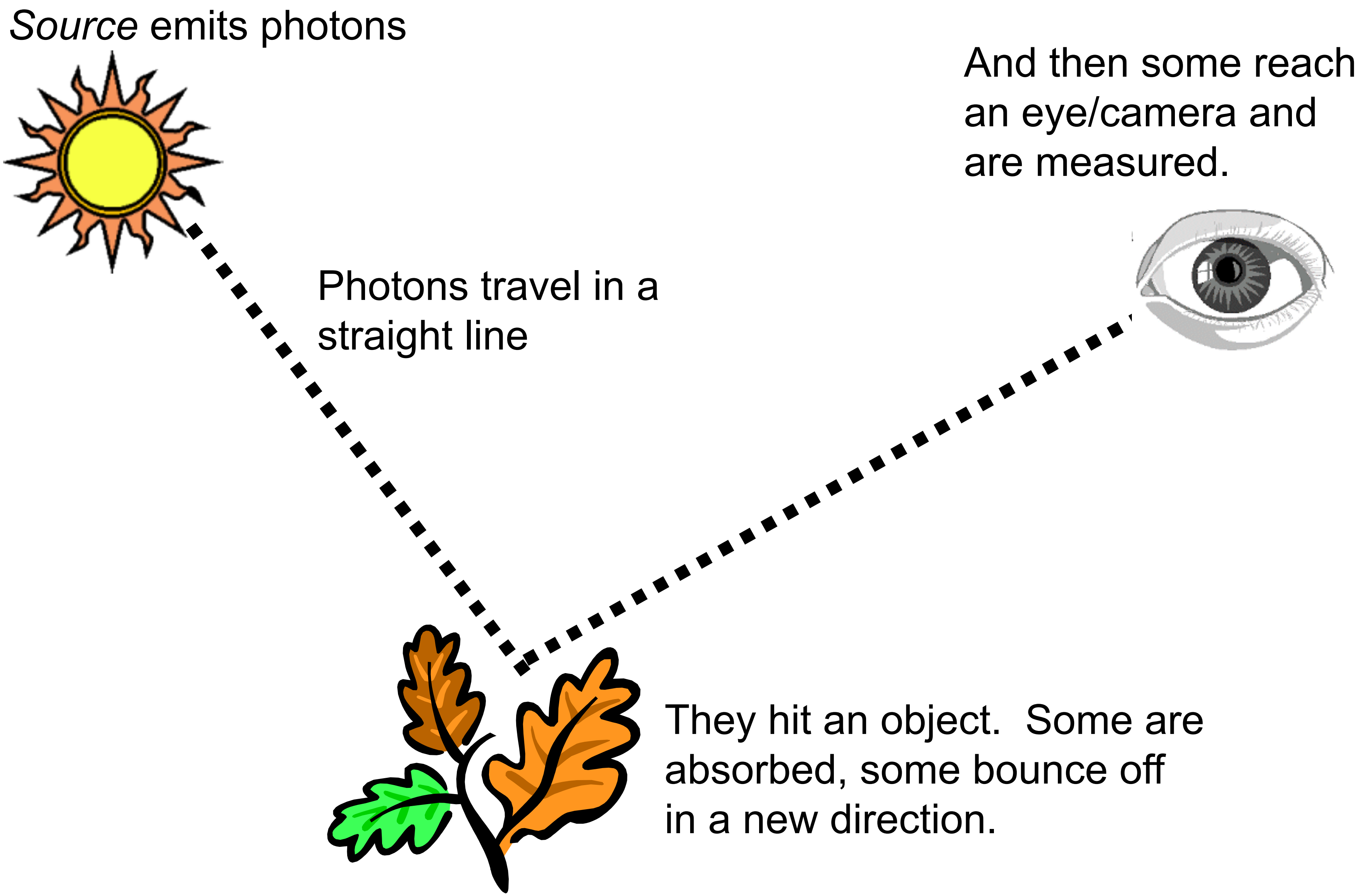
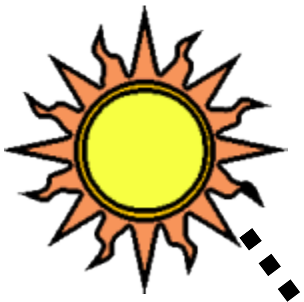
# Sketch: Light Transport



# Light Transport

*Source* emits photons



**Illumination**

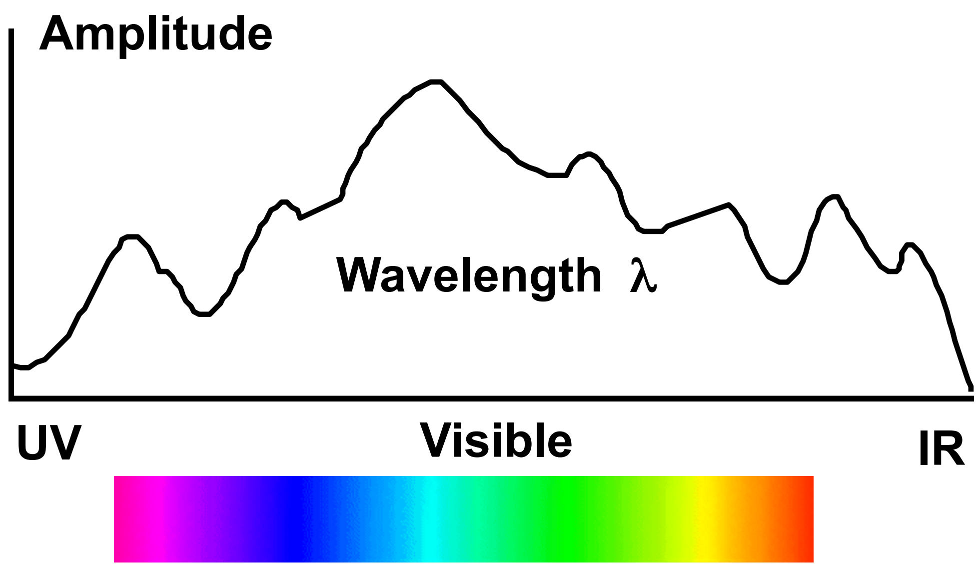
Photons travel in a straight line

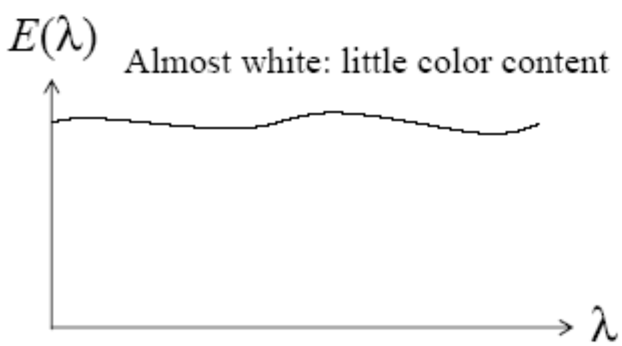
And then some reach an eye/camera and are measured.

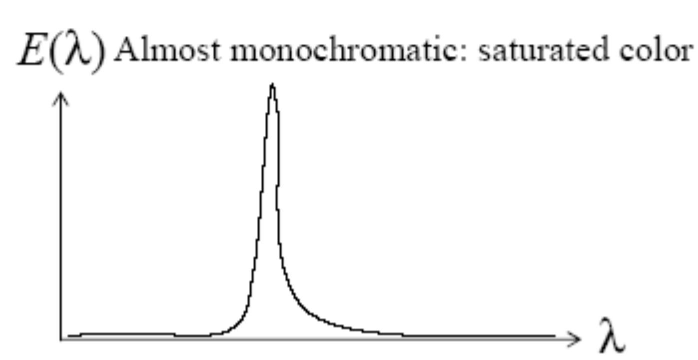
They hit an object. Some are absorbed, some bounce off in a new direction.

# Color of Light Source

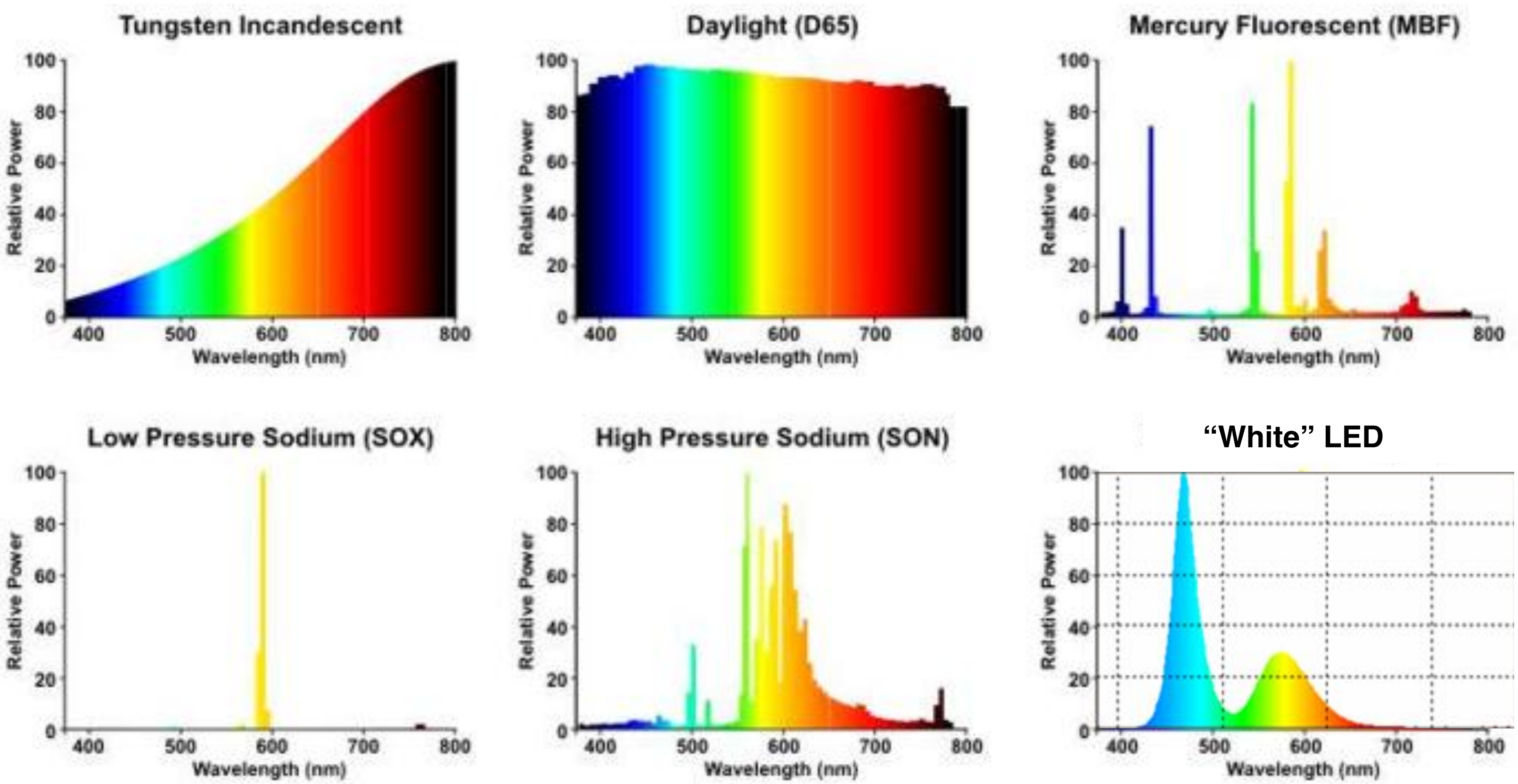
**Spectral Power Distribution:** Relative amount of light energy at each wavelength



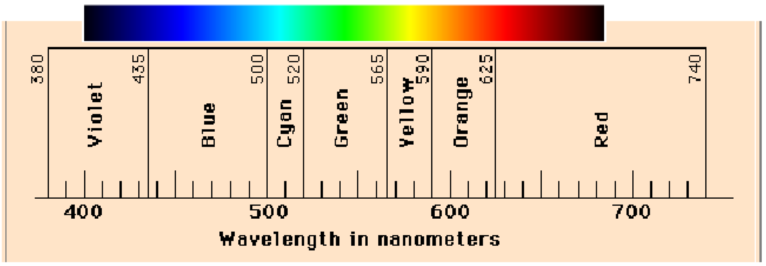



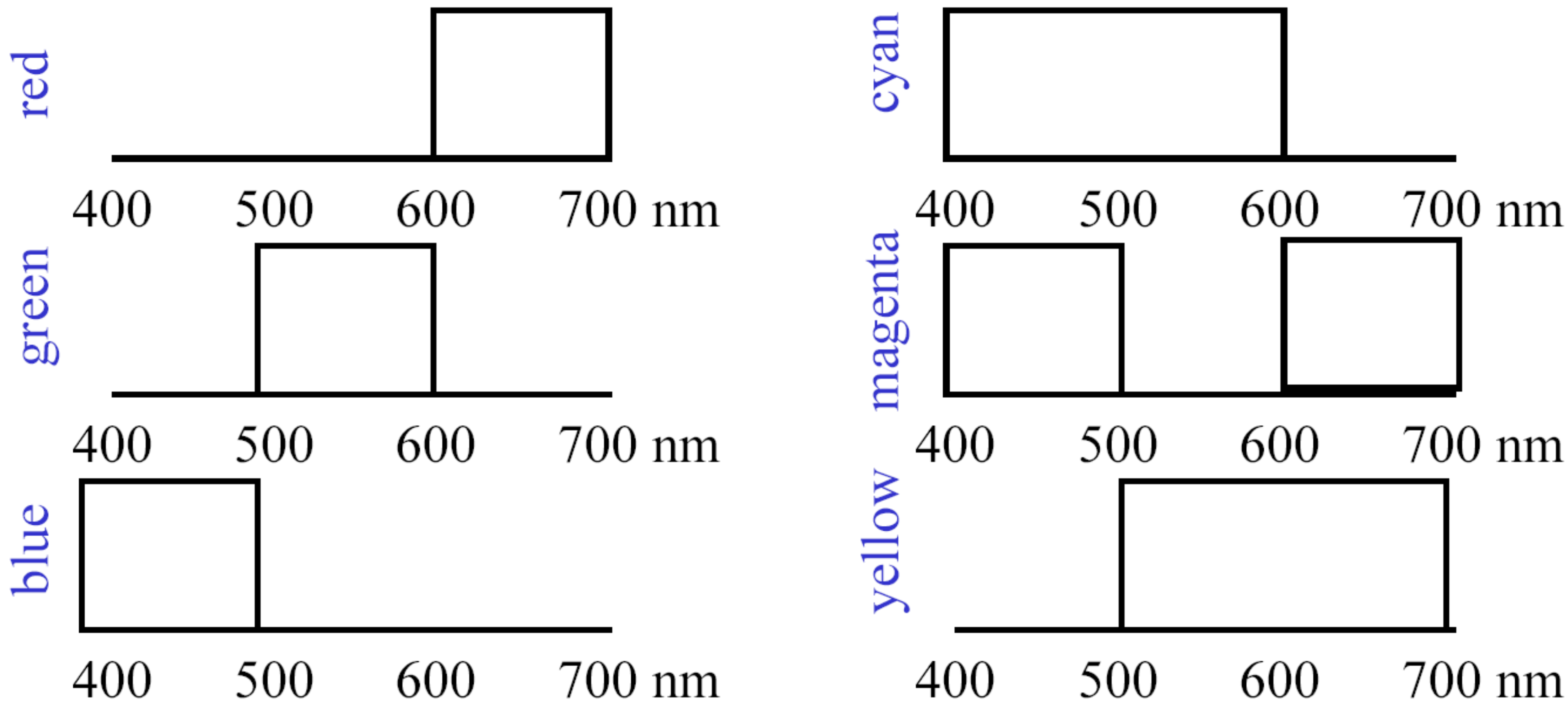



# Some Light Source SPDs

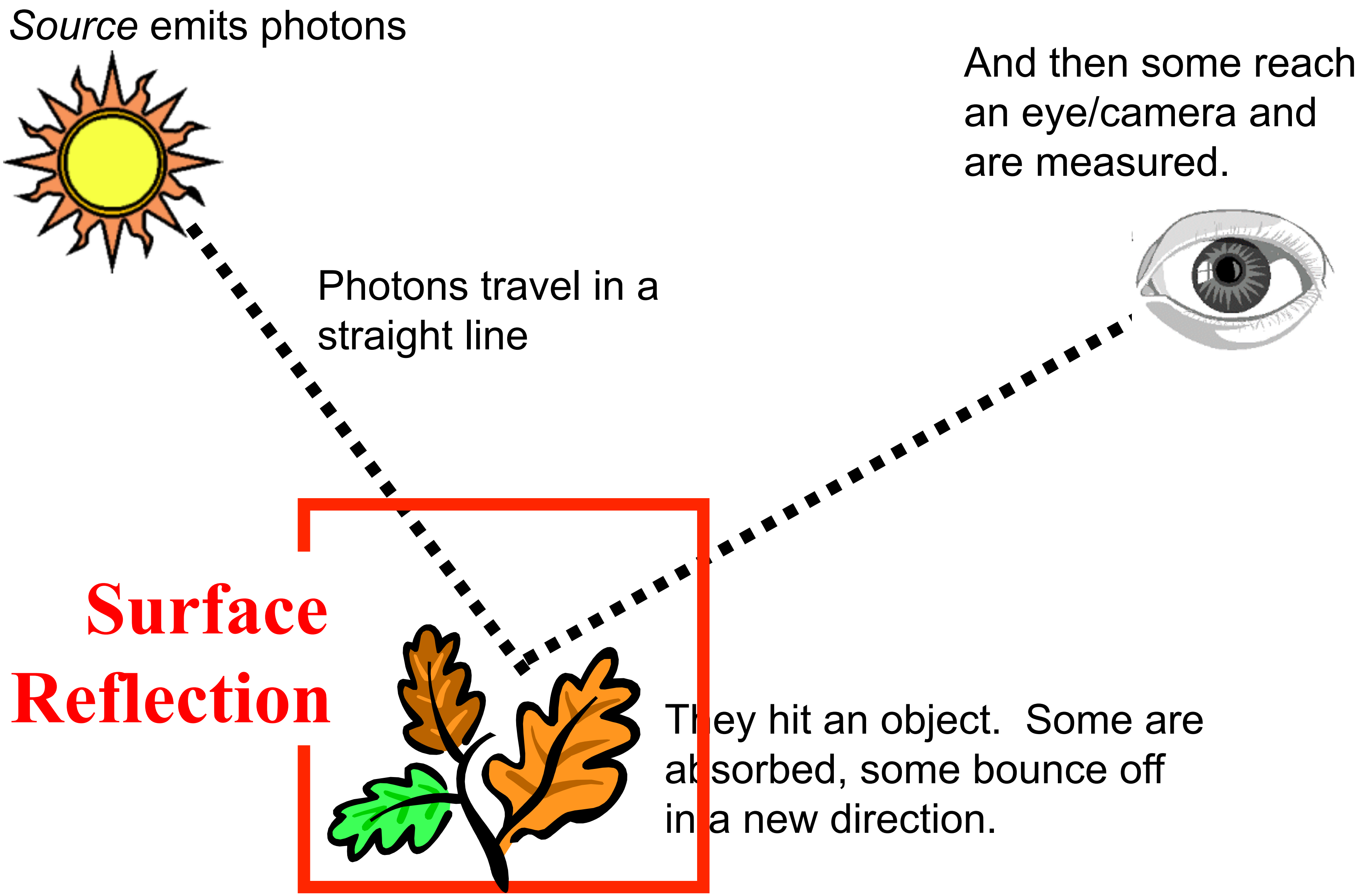


# Color names for cartoon spectra

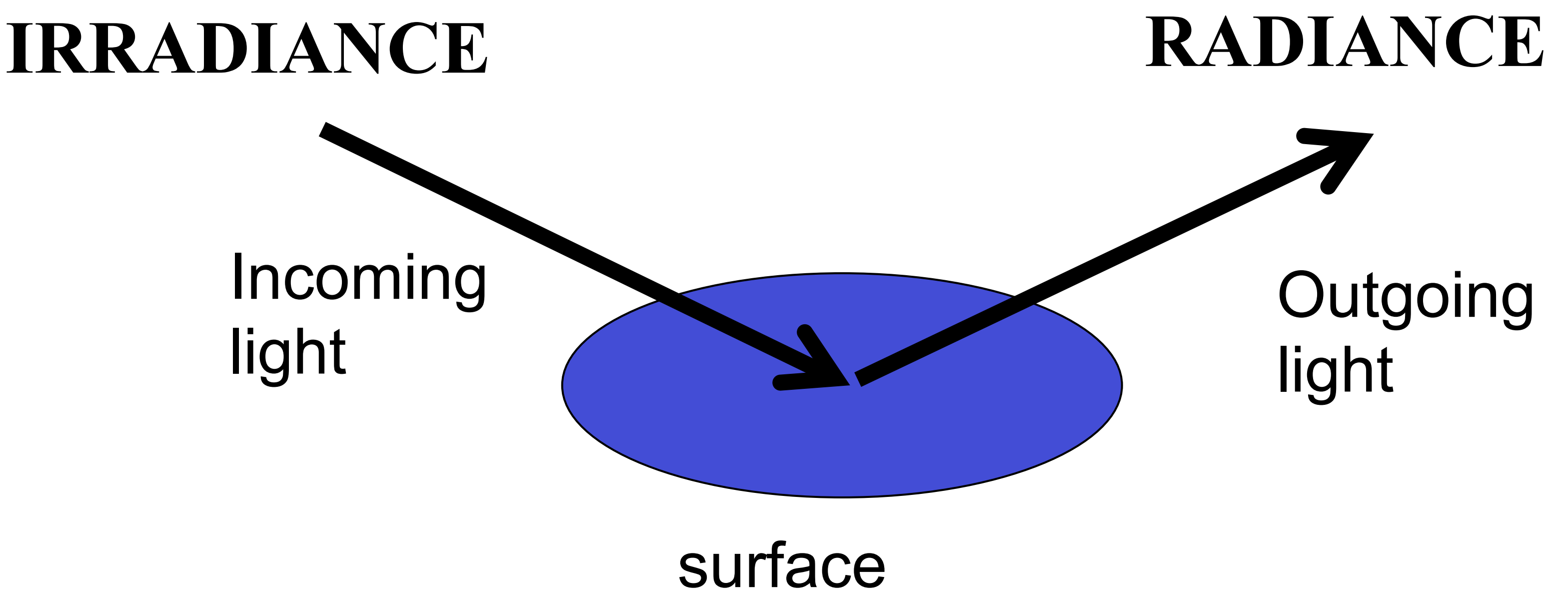


# Light Transport



# (Ir)radiance


IRRADIANCE
RADIANCE
Incoming light
Outgoing light
surface

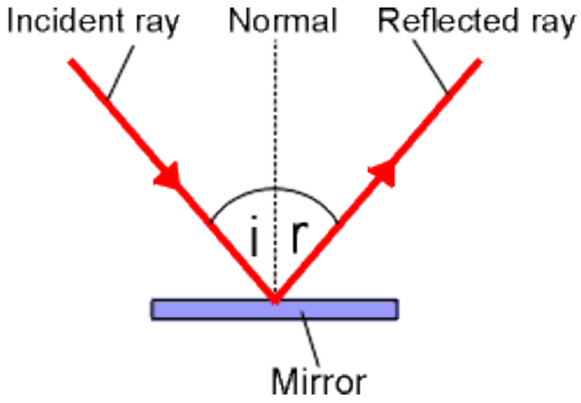
# Specular Surfaces

Light rays purely reflect via Snell's law (angle of reflection = angle of incidence)

**Properties:**

Outgoing light has same SPD ("color") as incoming light.

If you stand in the right place you see a little picture of the light source reflected off the surface.



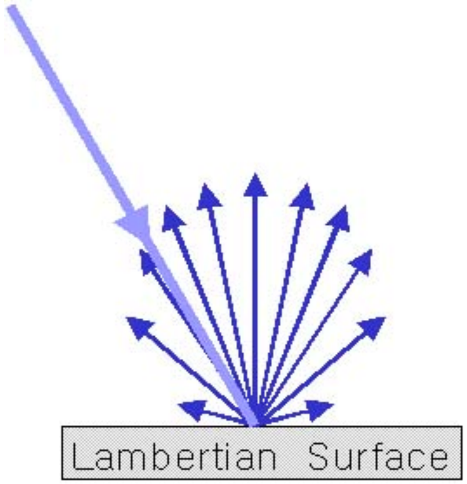
# Lambertian Surfaces

Purely “matte” surface.

**Properties:**

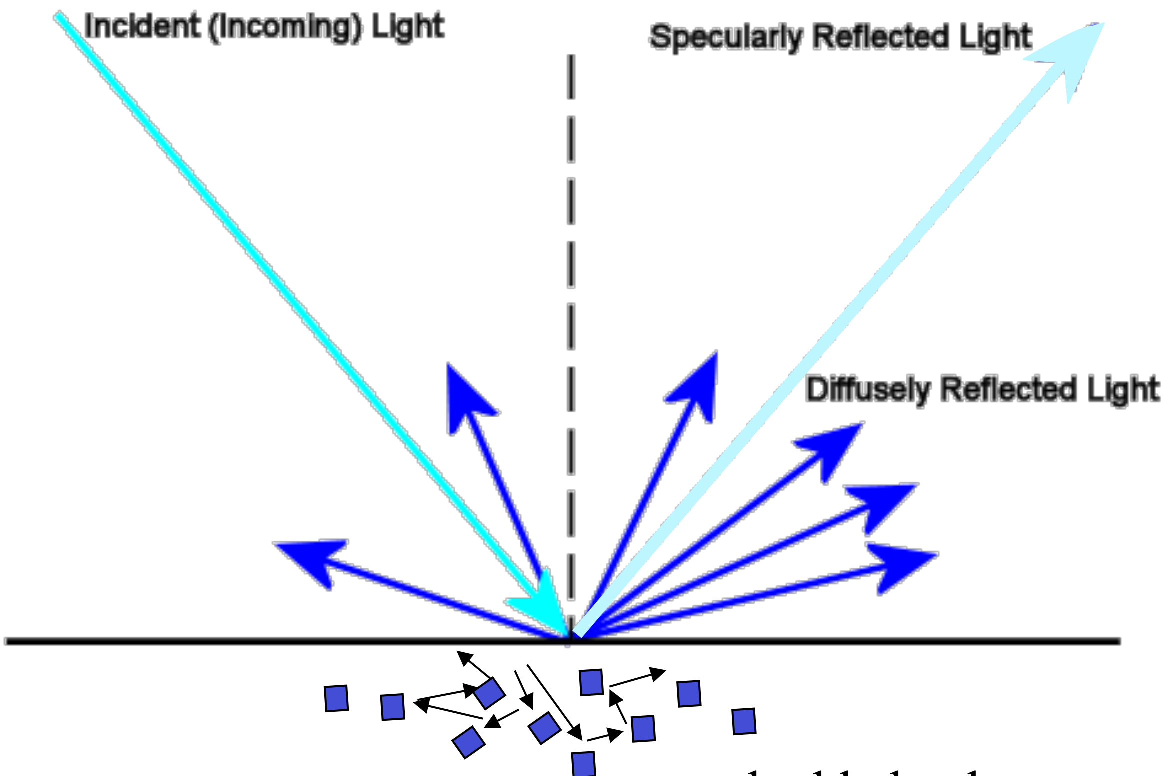
Apparent brightness is proportional to cosine of angle between observer’s line of sight and the surface normal (Lambert’s Law)

Outgoing light has SPD that depends on spectral albedo of surface (what wavelengths get absorbed vs transmitted).



# More General Surfaces

Have both specular and diffuse reflections.




embedded colorant
e.g. paint

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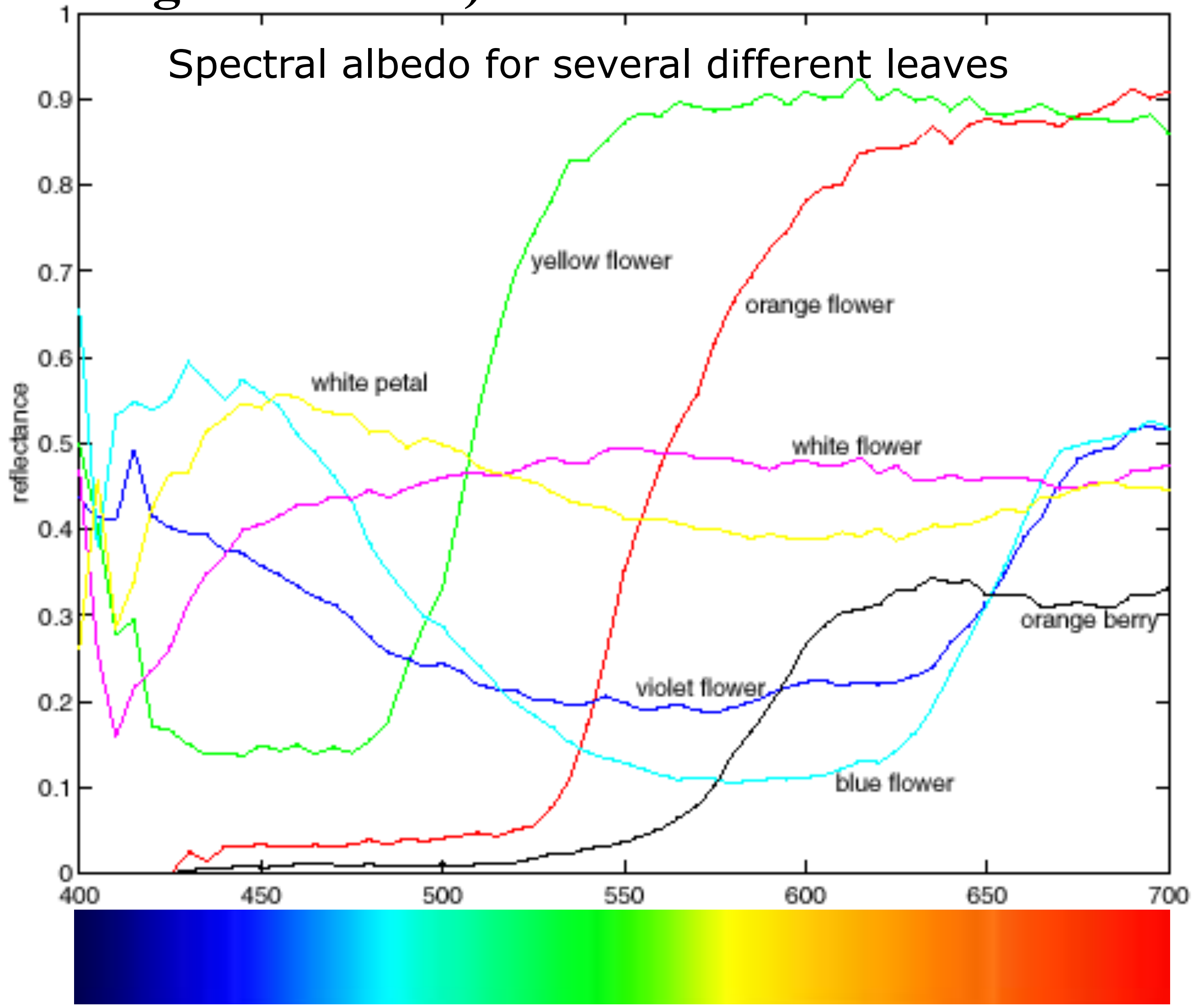
# Spectral Albedo

**Ratio of outgoing to incoming radiation at different wavelengths. (proportion of light reflected)**



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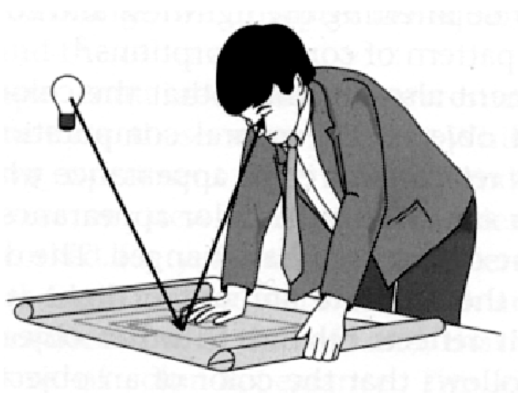
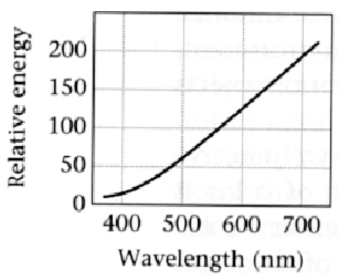
# Spectral Radiance



Often are more interested in relative spectral composition than in overall intensity, so the spectral BRDF computation simplifies to a wavelength-by-wavelength multiplication of relative energies.

**Spectral Irradiance**

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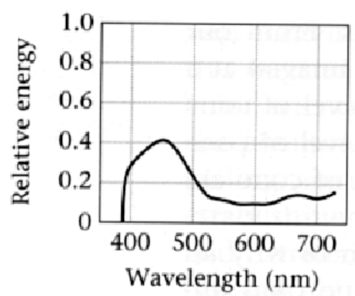
**Spectral Albedo**

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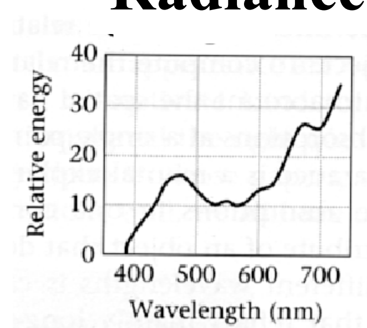
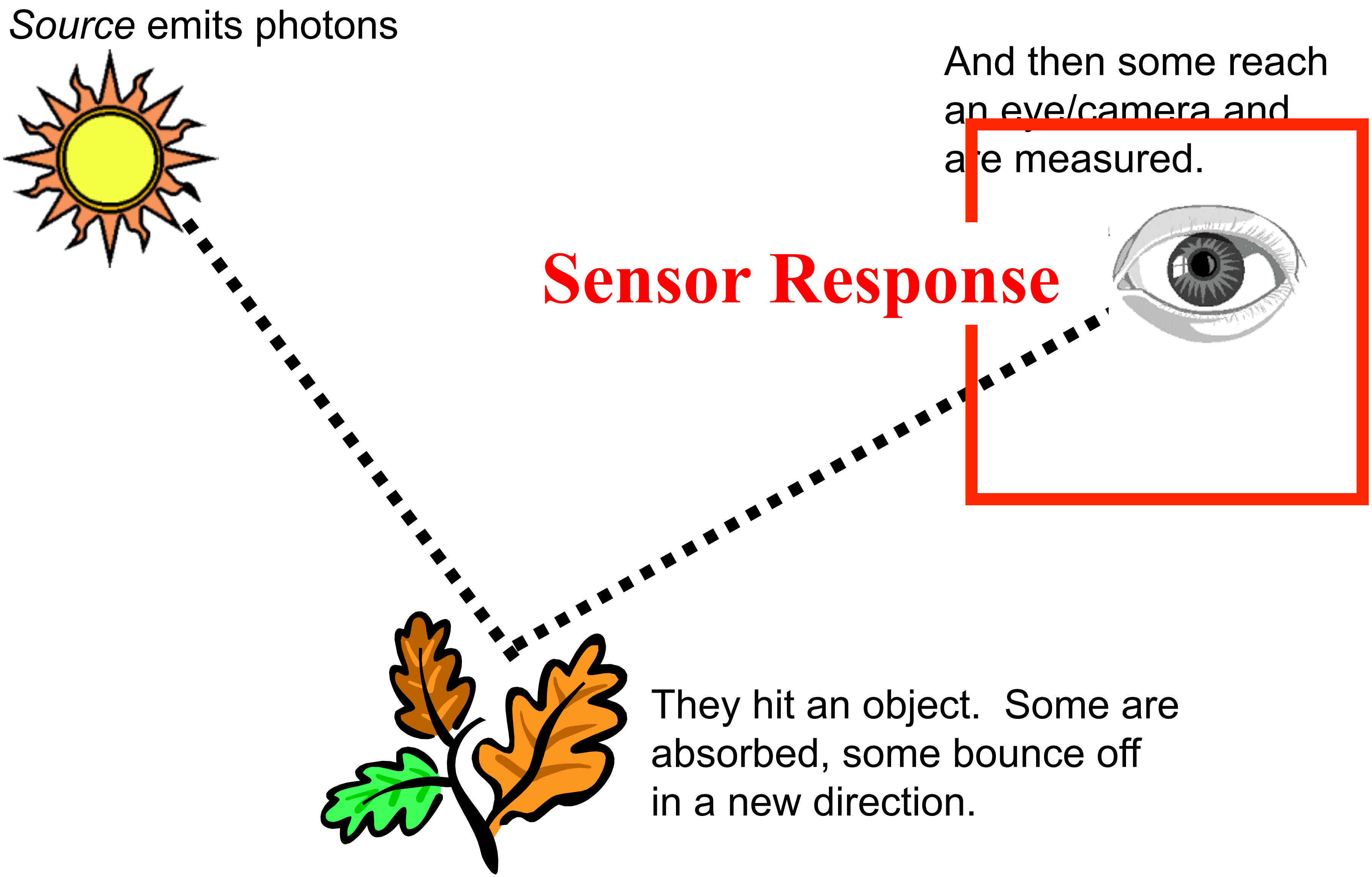
**Spectral Radiance**




Foundations of Vision, by Brian Wandell, Sinauer Assoc., 1995

# Light Transport



# Human Vision

- Human eyes have 2 types of sensors:
  - CONES
    - Sensitive to colored light, but not very sensitive to dim light
  - RODS
    - (very) Sensitive to achromatic light

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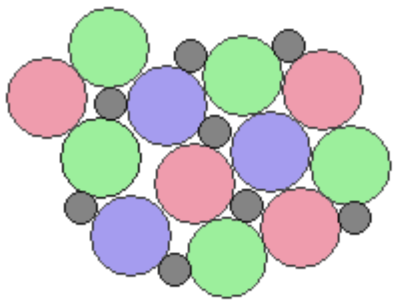
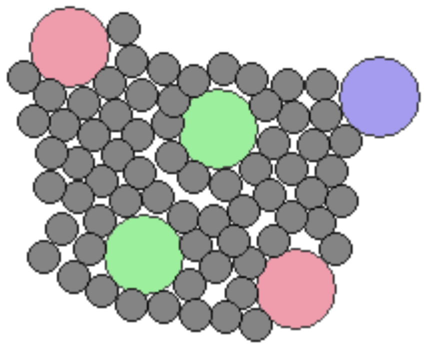
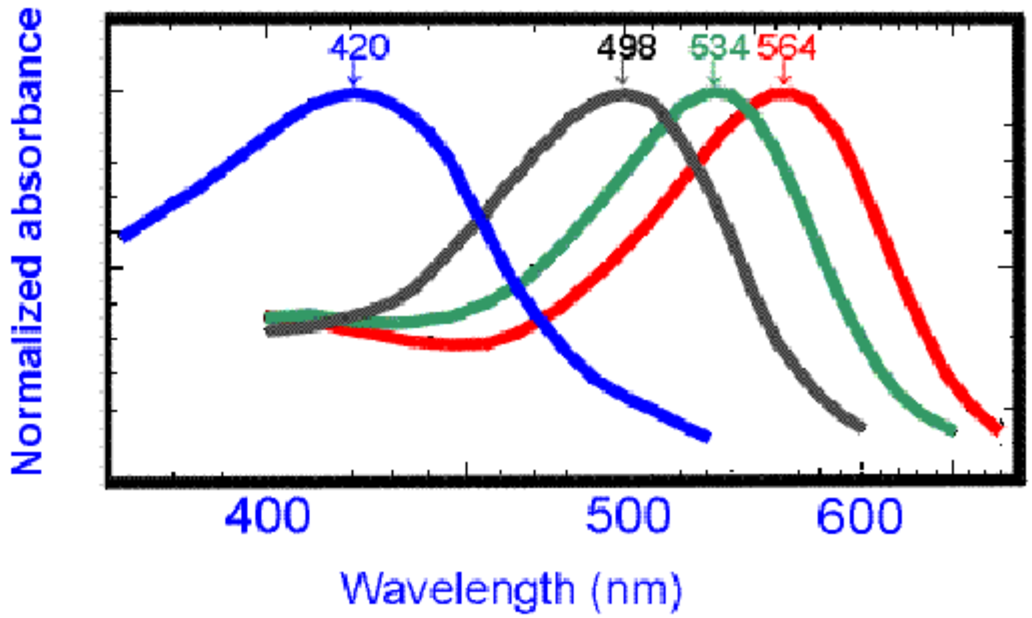
# Human Eye: Rods and Cones

near fovea





near periphery




After Bowmaker & Dartnall, 1980

- rods (overall intensity)
- S cones (blue)
- M cones (green)
- L cones (red)

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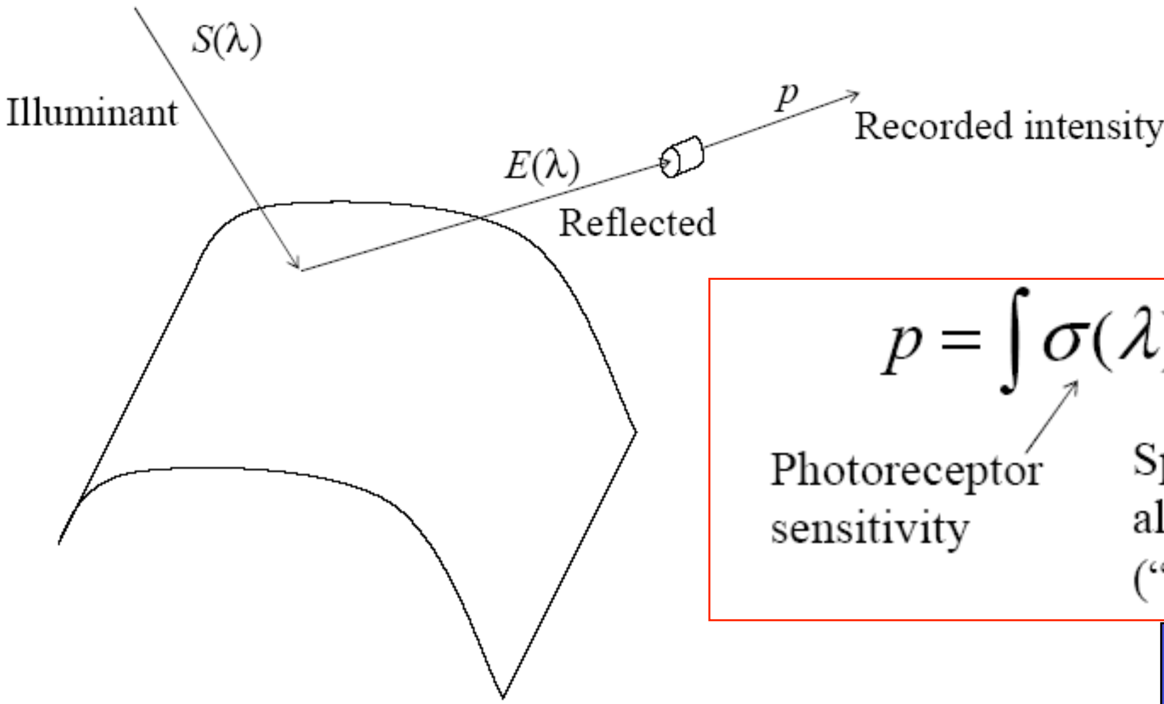
# Putting it all Together = Color




$$p = \int \sigma(\lambda)\rho(\lambda)S(\lambda)d\lambda$$

Photoreceptor sensitivity

Spectral albedo ("object color")

Illuminant color

3 cones

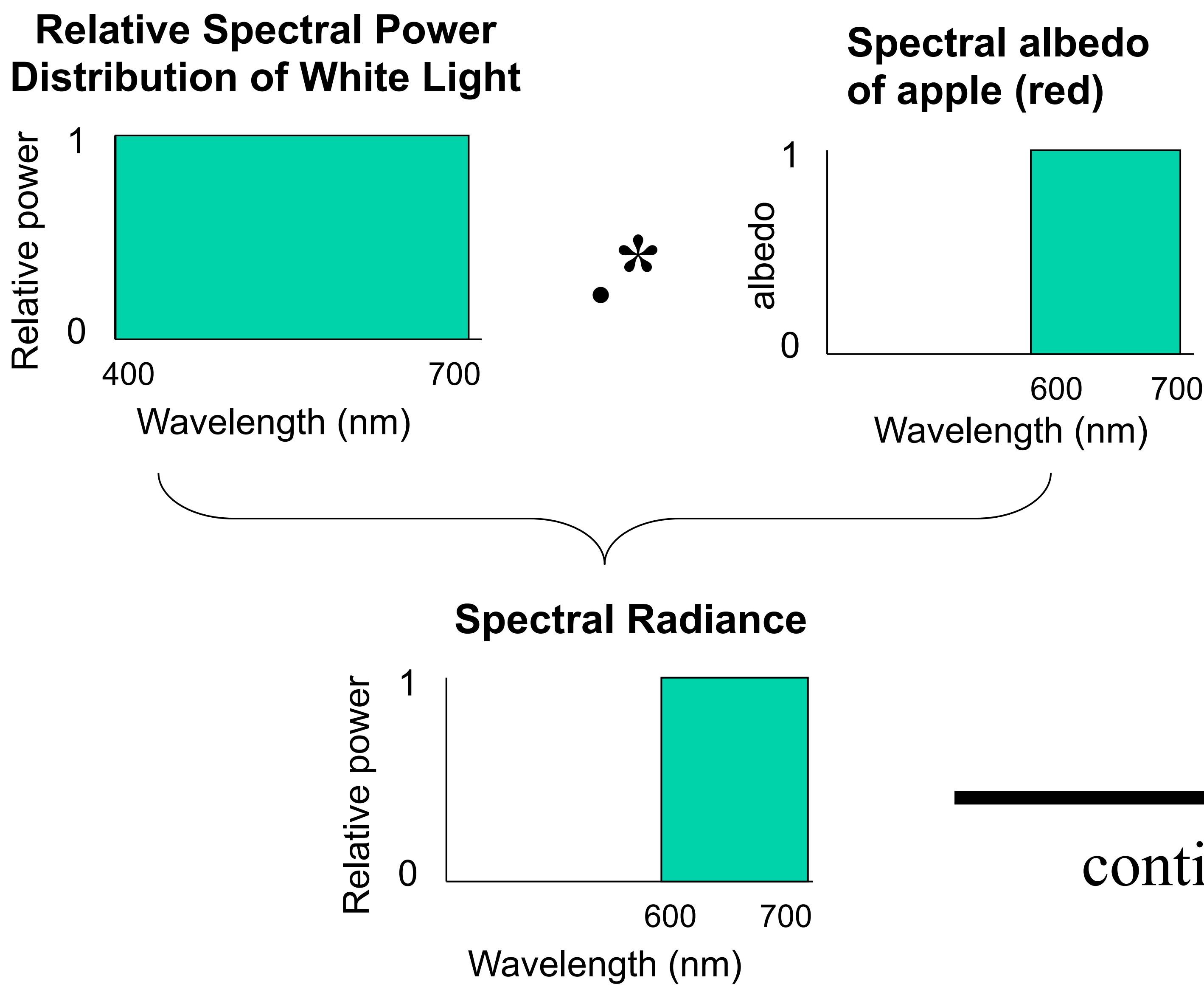
**COLOR!**

$$p_S = \int \sigma_S(\lambda)E(\lambda)d\lambda$$

$$p_M = \int \sigma_M(\lambda)E(\lambda)d\lambda$$

$$p_L = \int \sigma_L(\lambda)E(\lambda)d\lambda$$

# Simple Example

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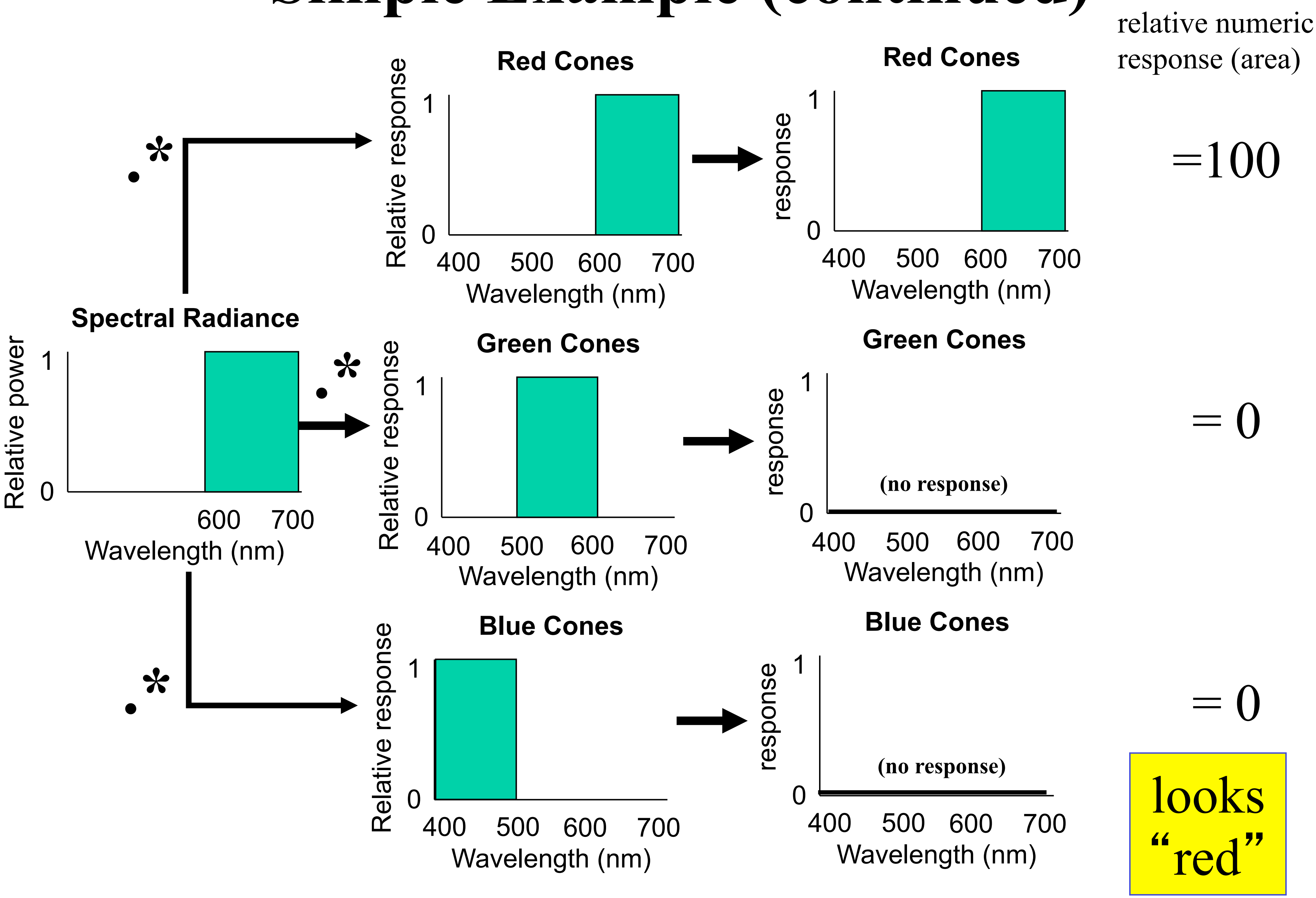
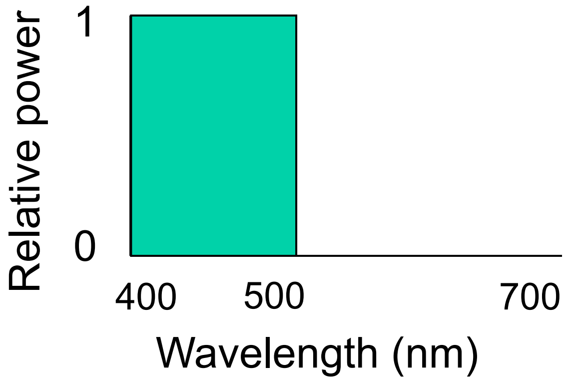
# Simple Example (continued)



# Simple Example

**Relative Spectral Power Distribution of Blue Light**

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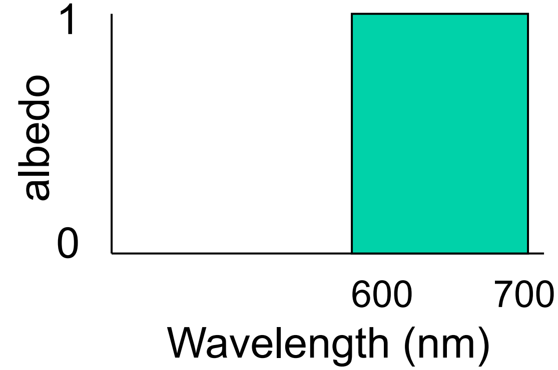
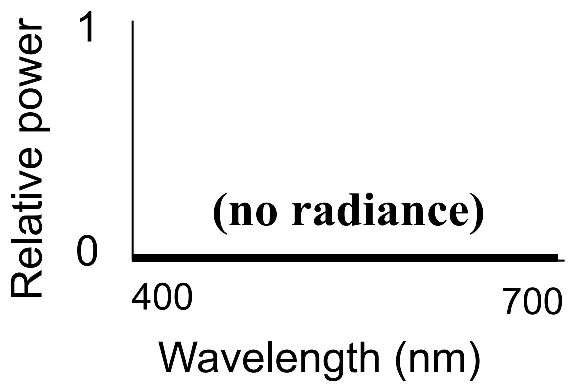
**Spectral albedo of apple (red)**




**Spectral Radiance**

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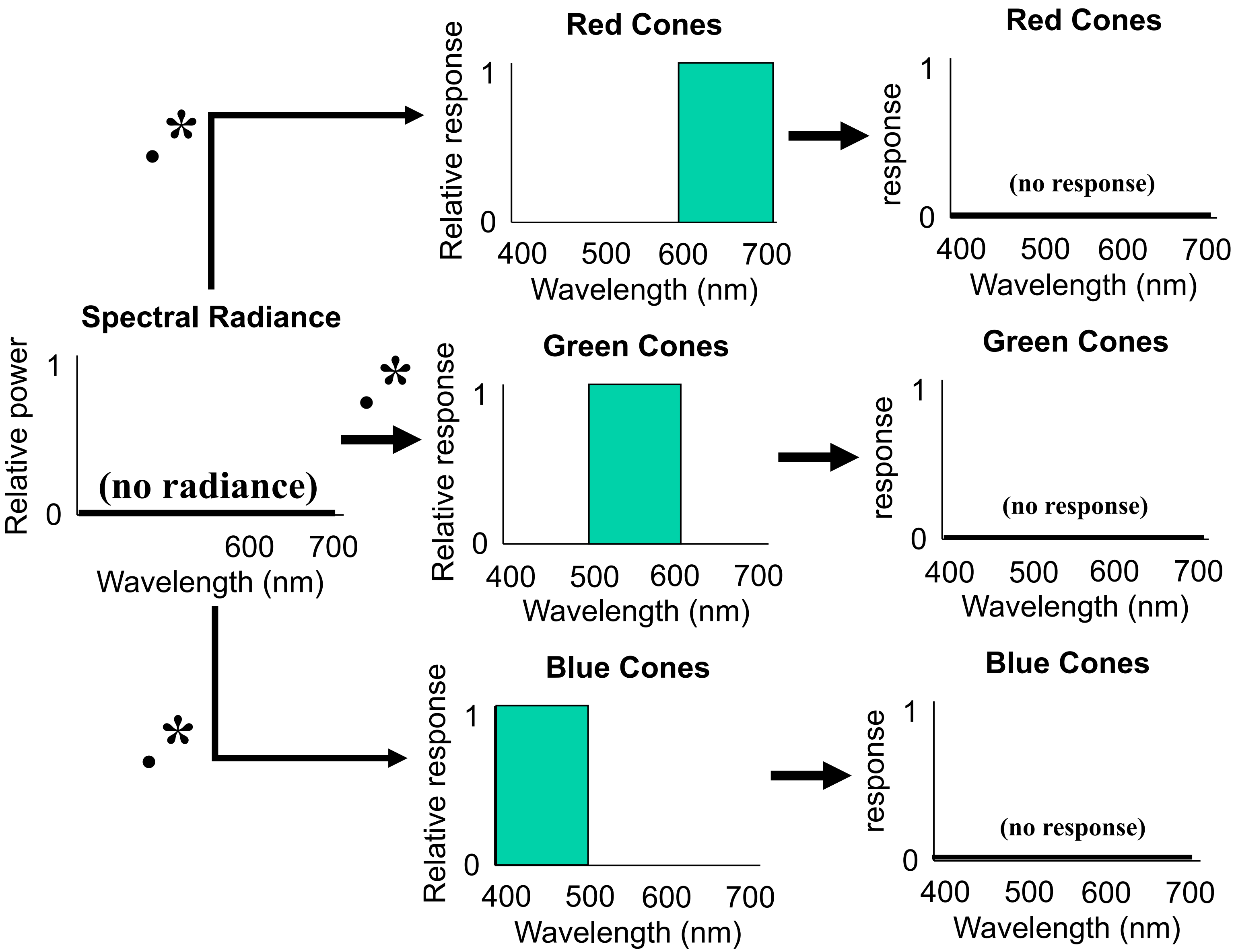
# Simple Example (continued)

relative numeric response (area)




$= 0$

$= 0$

$= 0$

looks "black"

# The Abyss Clip

## “One-way ticket” clip from DVD

# What is Going On in This Clip?

Under yellowish green light,
both the blue/white wire and the
black/yellow wire look identical.

Now for the spectral explanation
of why this happens…

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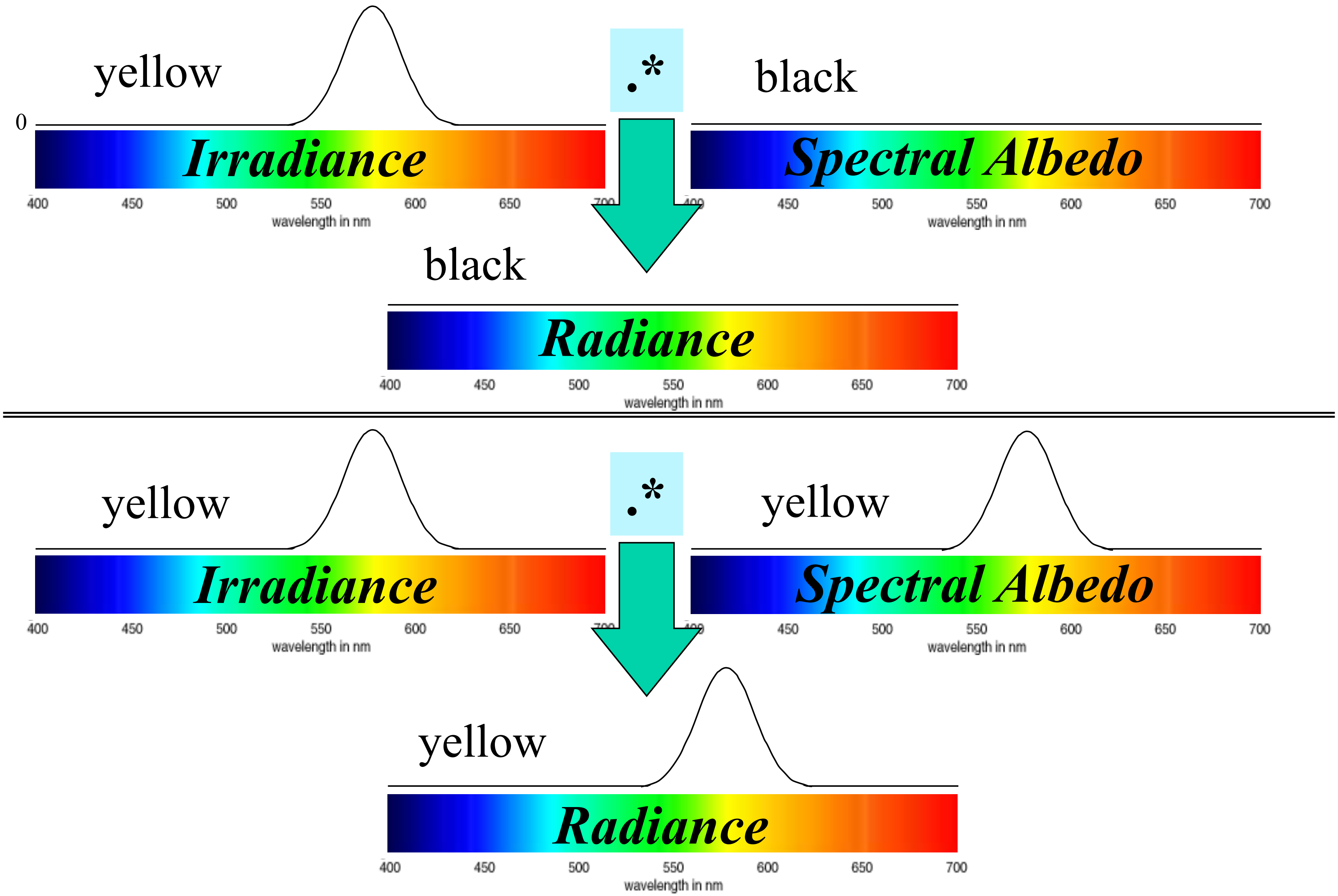
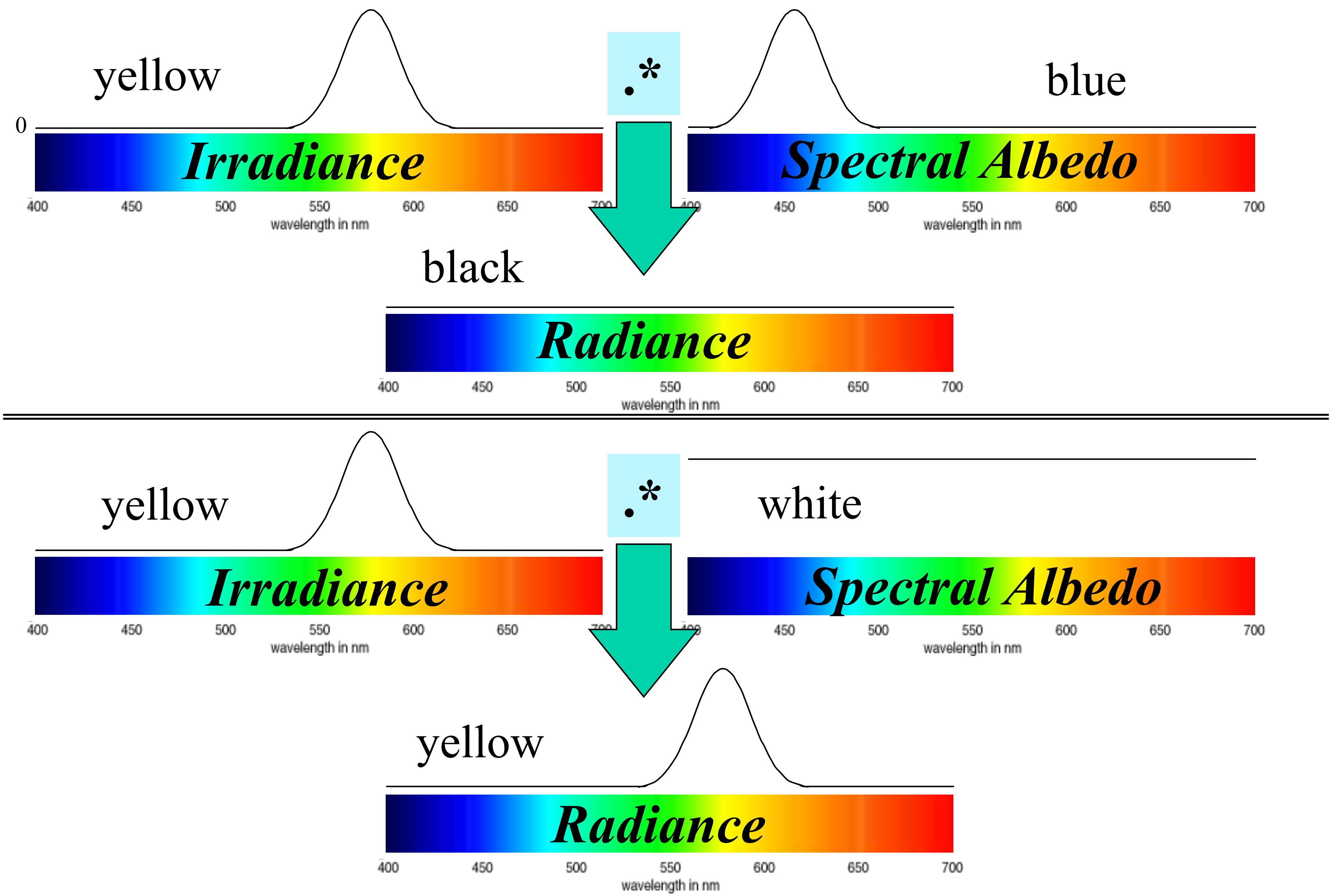
# Black/Yellow under Yellow Light



# Blue/White under Yellow Light



# Lesson Learned

Surfaces materials that look different under white light can appear identical under colored light.

# Metamers

Definition: two different spectral reflectances that appear indistinguishable to a given observer under given illumination conditions.

Illumination metamerism: two color distributions look the same under a given illumination

Observer metamerism: two color distributions look the same to a given observer.

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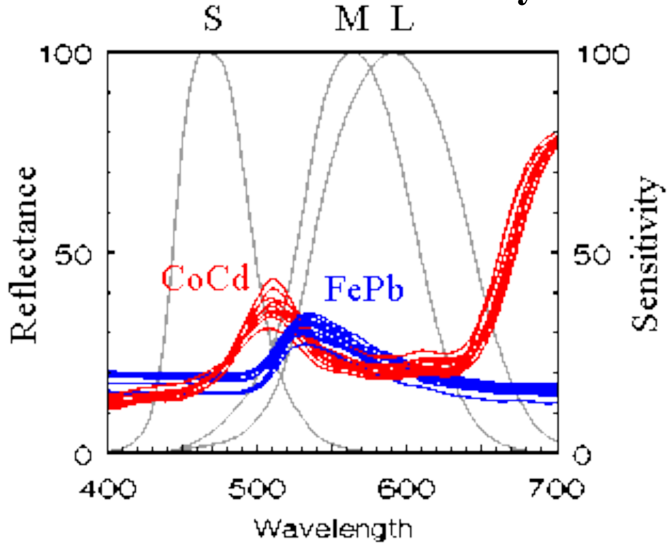
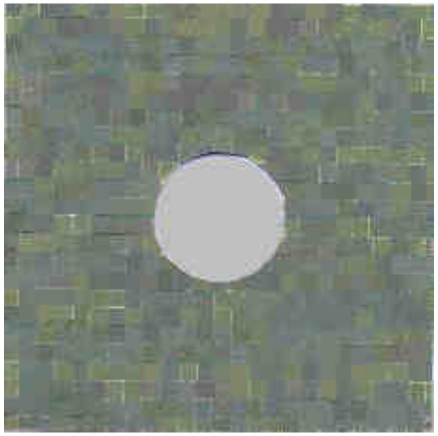
# Sample Metamers

**Metameric curves for human eye under daylight**

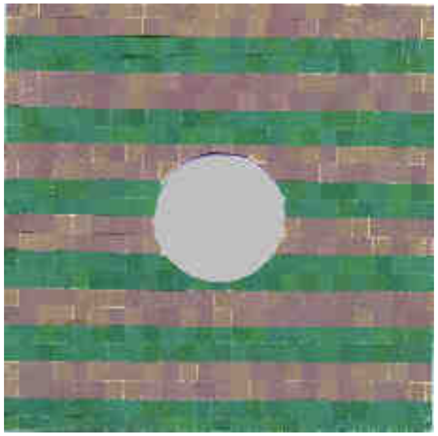



**Test pattern viewed under daylight**



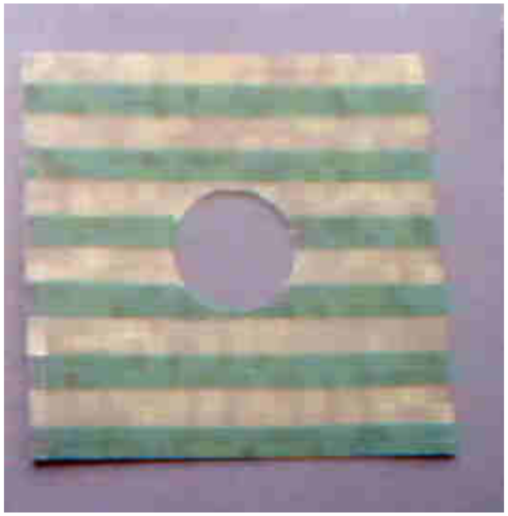
**Overcoming metamerism by viewing under different illumination**

**Viewed under incandescent lighting**



**Overcoming metamerism by having a different observer**

**Viewed by camera with more sensitive red response than human eye**



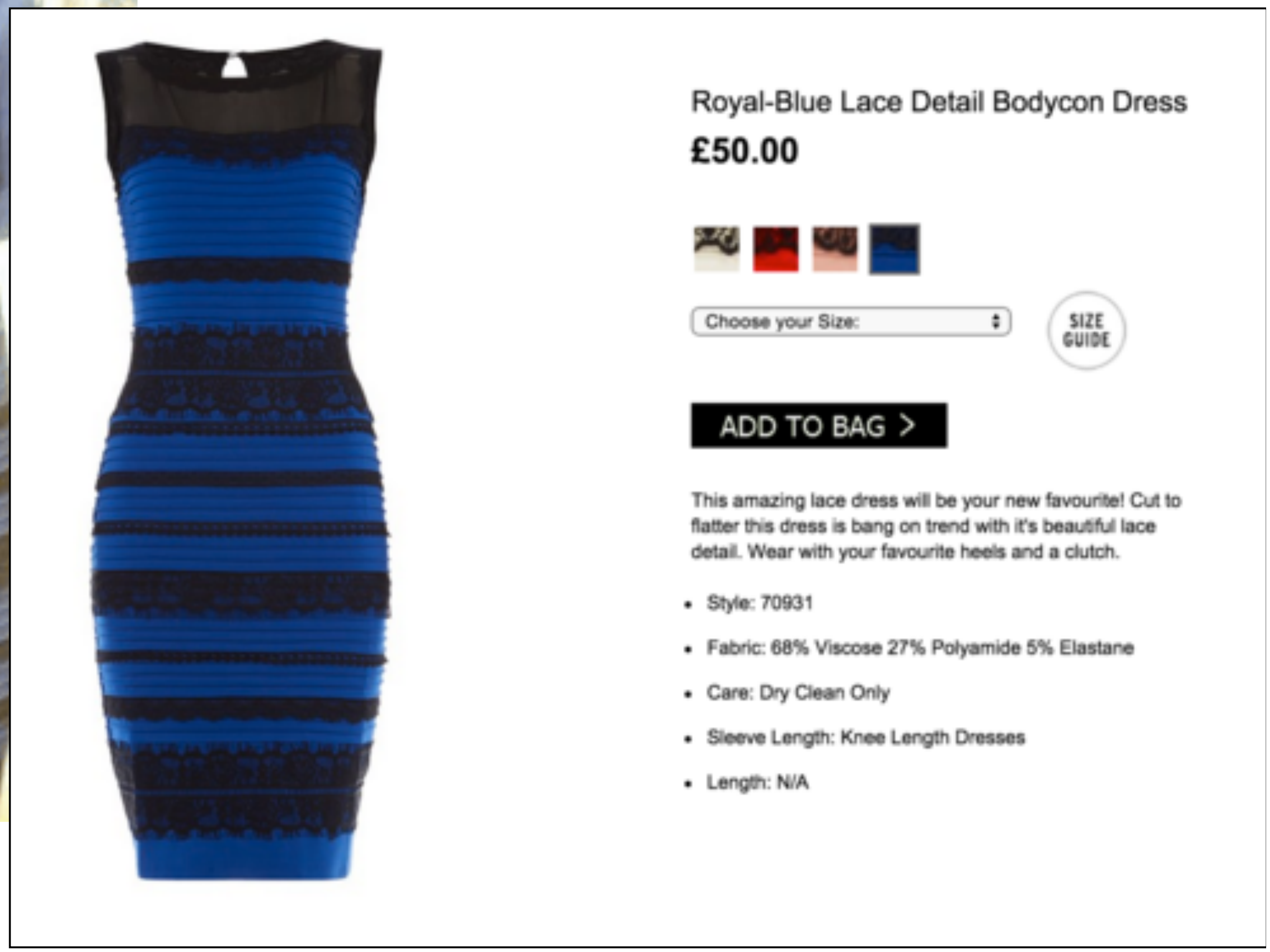
From http://www.iitp.ru/projects/posters/meta/

# What Color is the Dress?

**Blue and black?**
**White and gold?**

Humans are not always good at identifying material colors under unknown illumination and sensor response, especially when there is not much context.

# What Color is the Dress?



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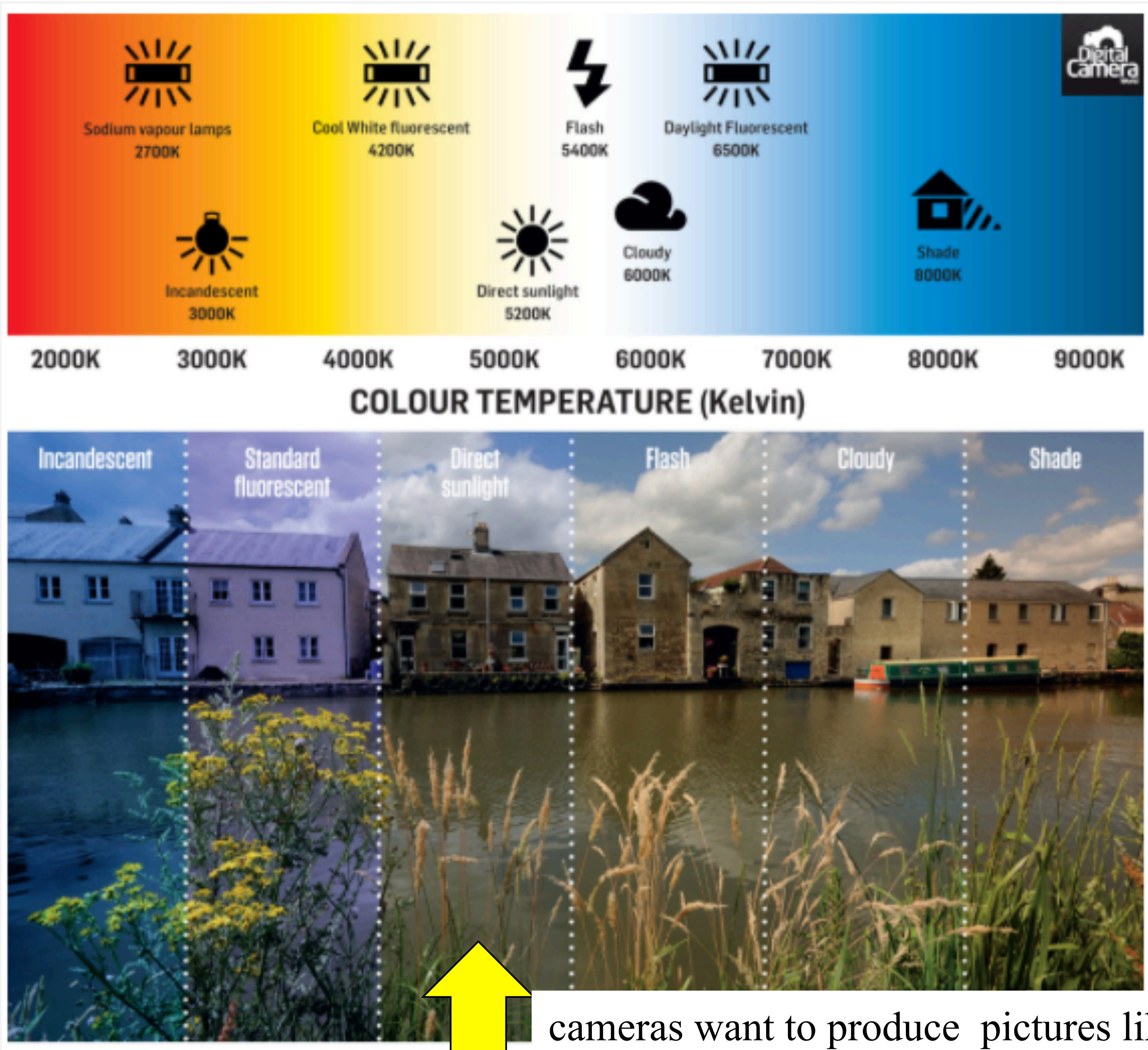
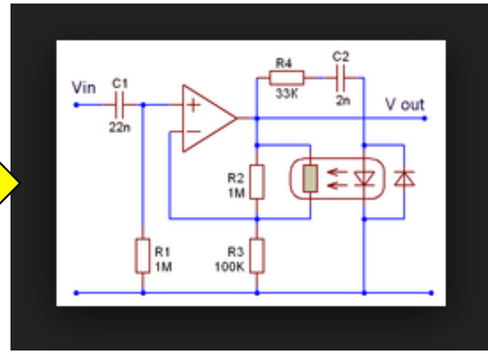
# My Take: Sensor Auto-Controls



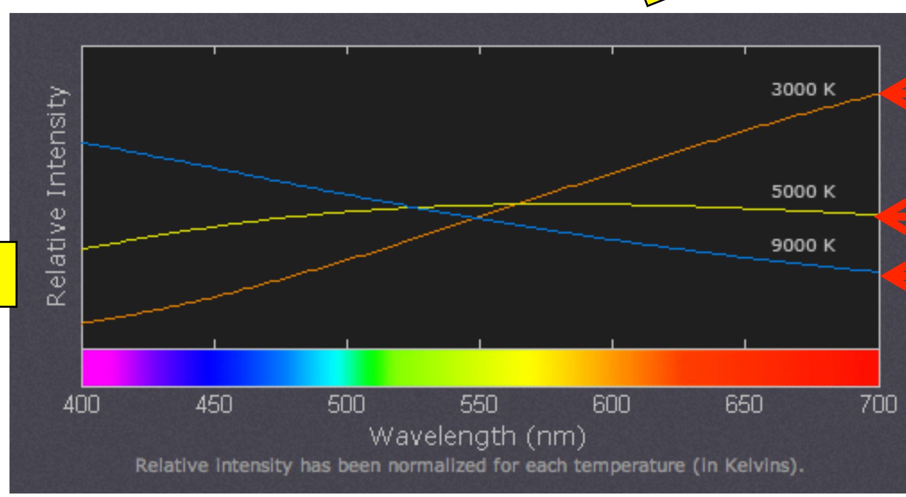

cameras want to produce pictures like this

# One Possible Explanation

Auto gain




Auto white balance




Ends up making it red-shifted

Tries to correct to neutral light

Thinks lighting is blue-shifted

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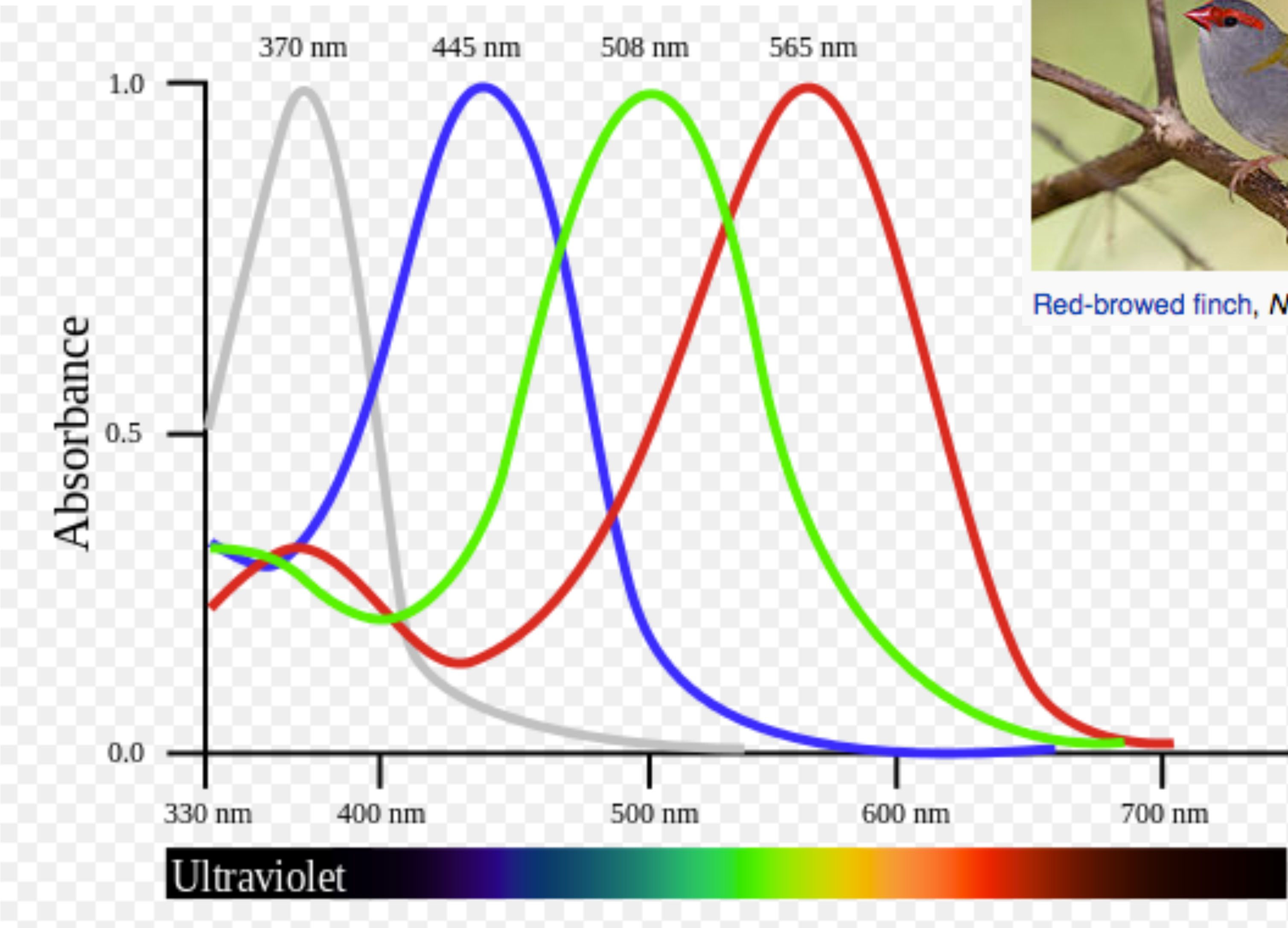
# Small Digression

Some animals can see ultraviolet light




Red-browed finch, *Neochmia temporalis*

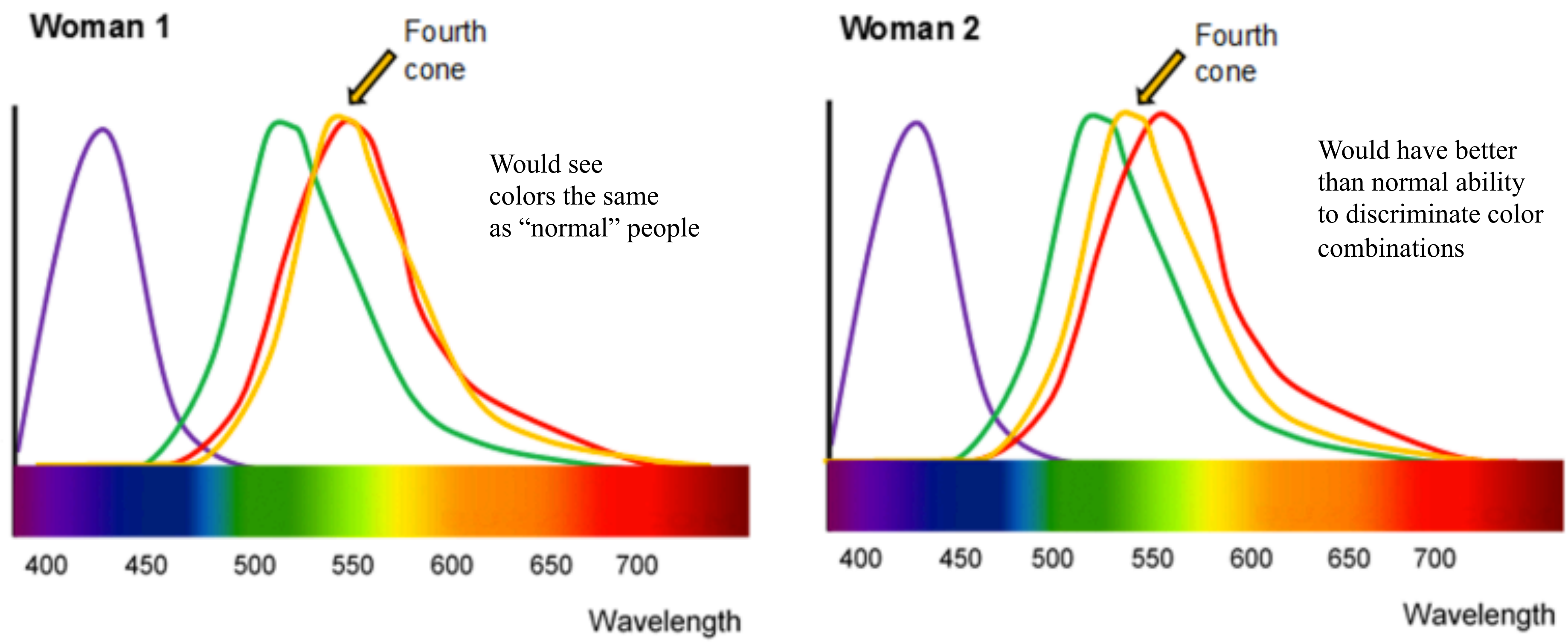
# Small Digression

**Flowers in Visible light (top) versus Ultraviolet light (bottom)**

http://www.naturfotograf.com/index2.html

# Small Digression

Tetrachromacy in humans: roughly 1 in 12 women have 4 types of cones! Sadly, only a very few of those have “superhuman” color discrimination abilities. But it is interesting that some do.




https://theneurosphere.com/2015/12/17/the-mystery-of-tetrachromacy-if-12-of-women-have-four-cone-types-in-their-eyes-why-do-so-few-of-them-actually-see-more-colours/

# Color Blindness

Normal color perception

Red/Green color blindness