How do we see *things*?

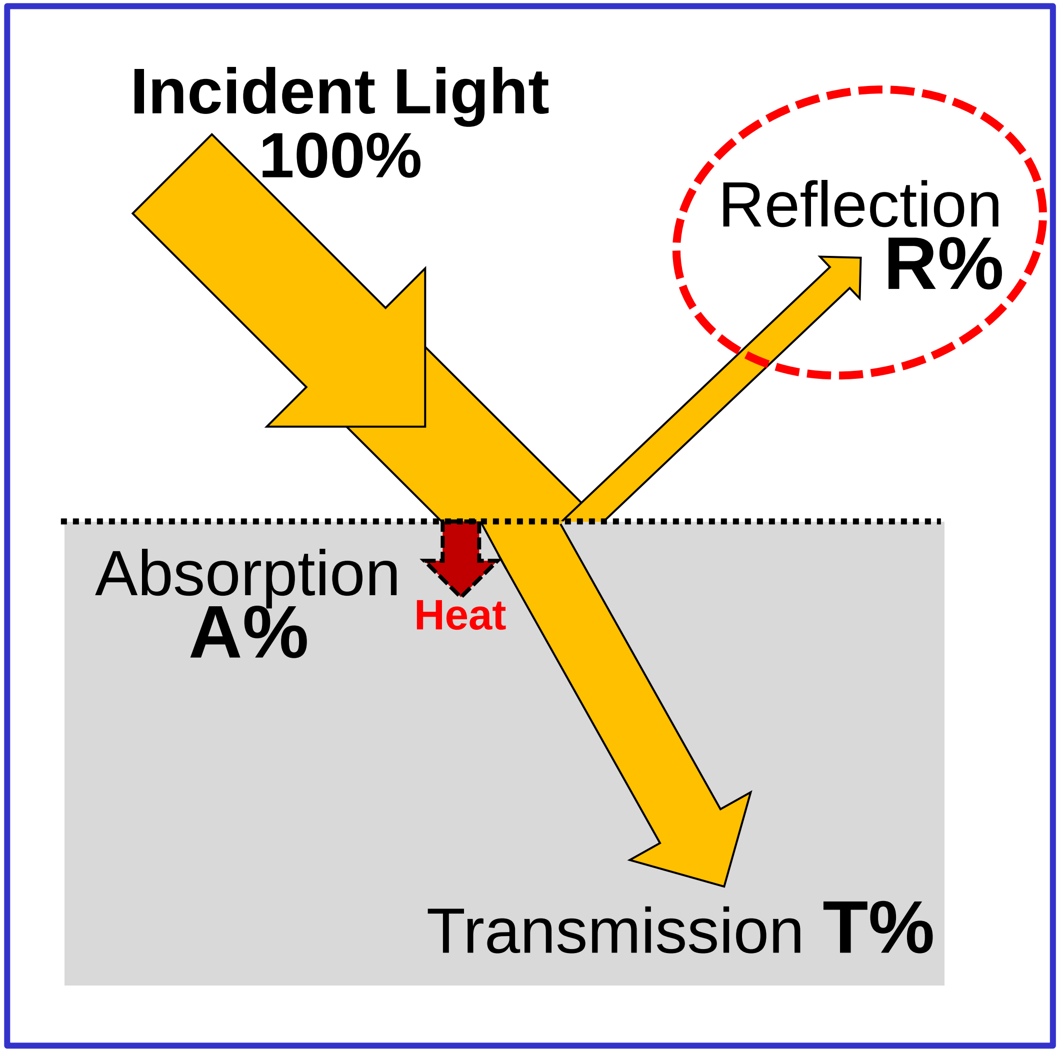
- When we see, we *sense light*.
- When we see an object, the light that reaches our eyes can come from <u>two different processes</u>:

1. The light can be <u>emitted directly from the object</u> (object=light source), like a light bulb or glow stick.

2. The light can come from somewhere else, like the Sun, and get <u>reflected by the object</u>.

Most of the objects that we see are visible from diffuse reflection.

Light Interaction with Non-Luminescent Matter

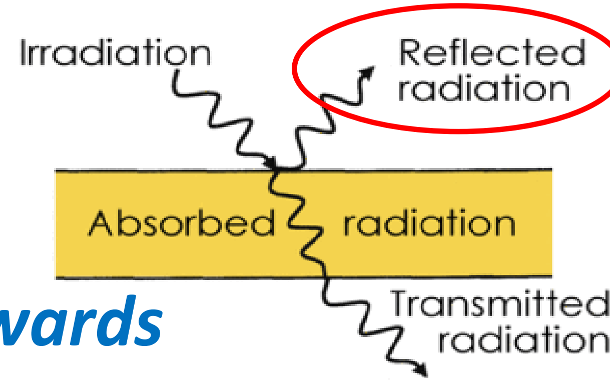


- **<u>Combination</u> of transmission, reflection, and absorption:**

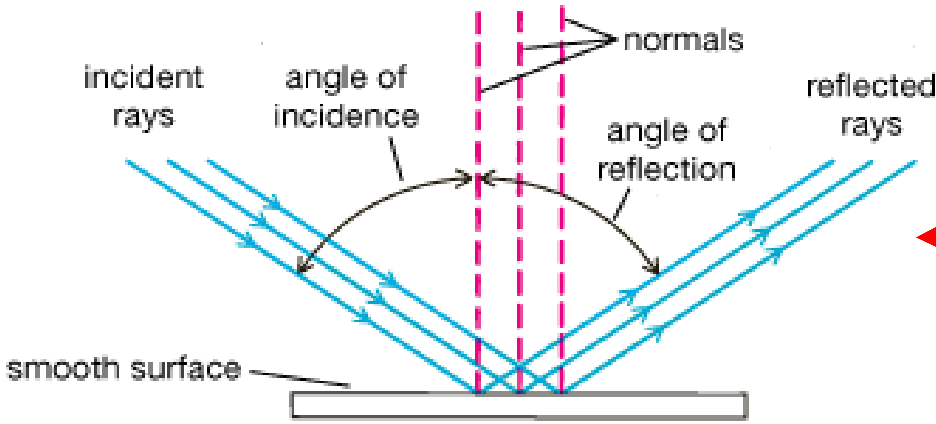
T%+R%+A%=100%

- **No material is 100% transparent.**
- **No material is 100% absorbing either.**

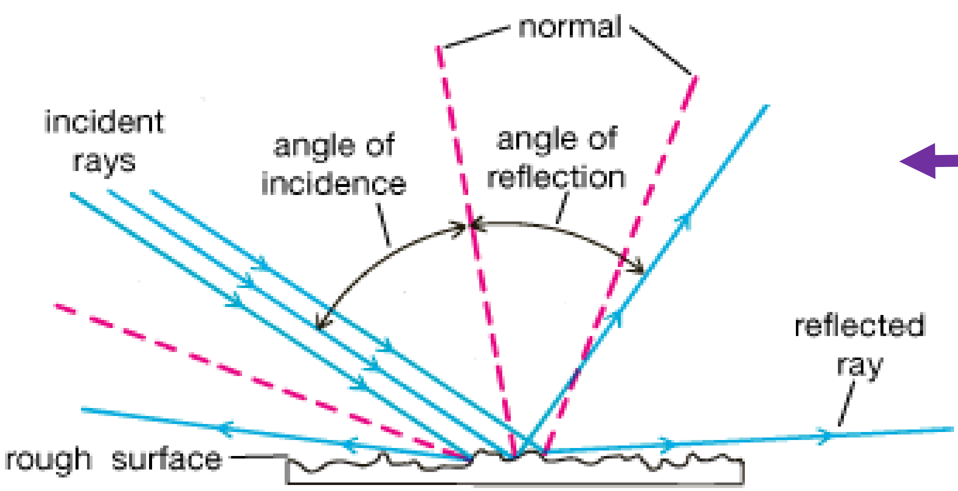
Reflection



bouncing of light off the surface,
change in the direction of travel *backwards*



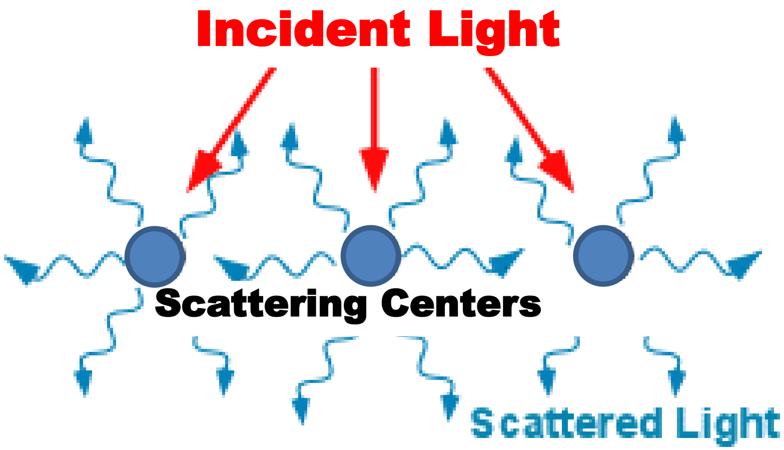
- **Specular reflection:** **if a <u>surface is perfectly smooth</u>, rays of light move out in definite directions.**



- **Diffuse reflection:** **if a <u>surface is not smooth</u>, the light rays are *scattered* in many random directions by microscopic details (irregularities).**

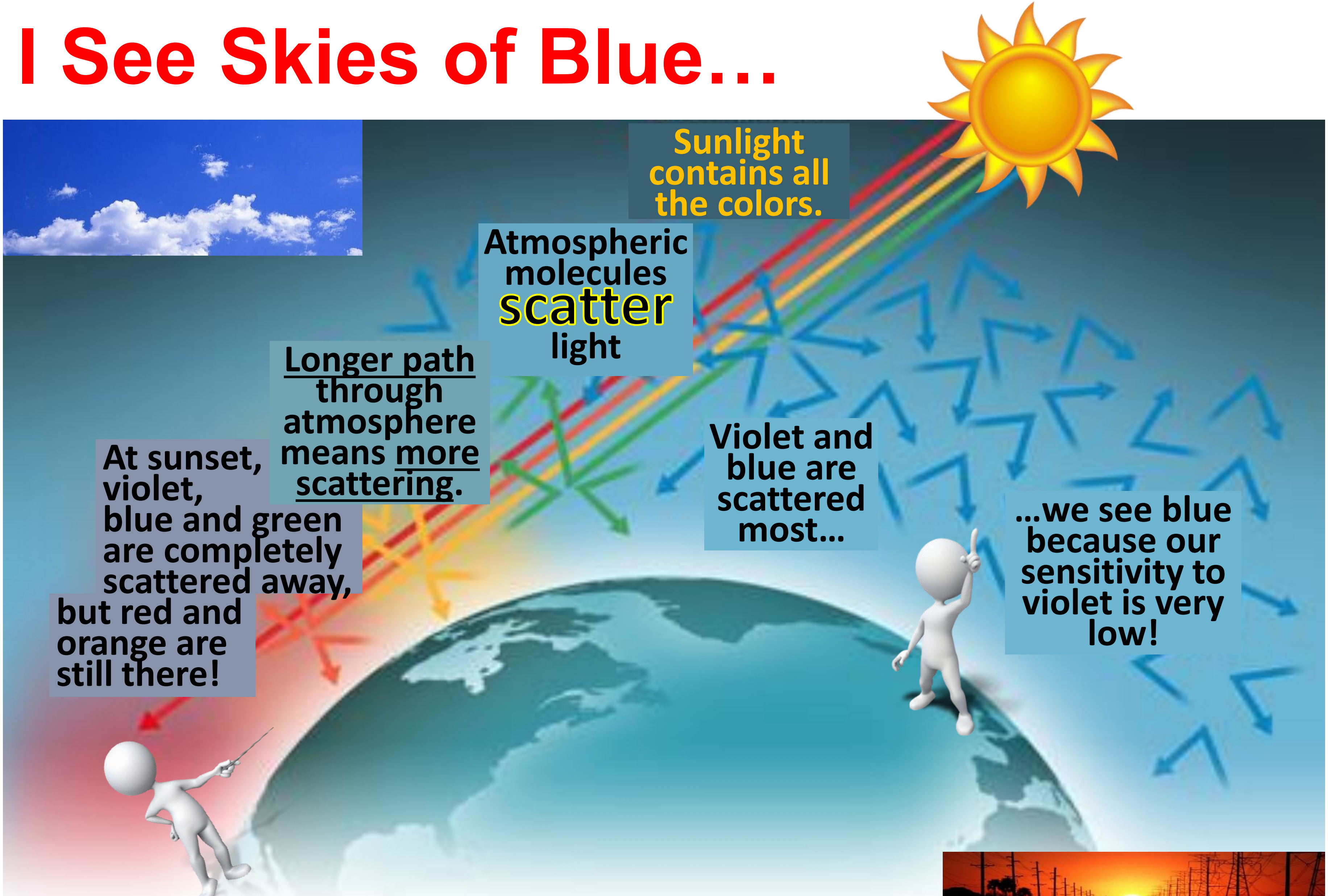
Scattering

light ray moves over to the side in all directions rather than forward, backward or being absorbed



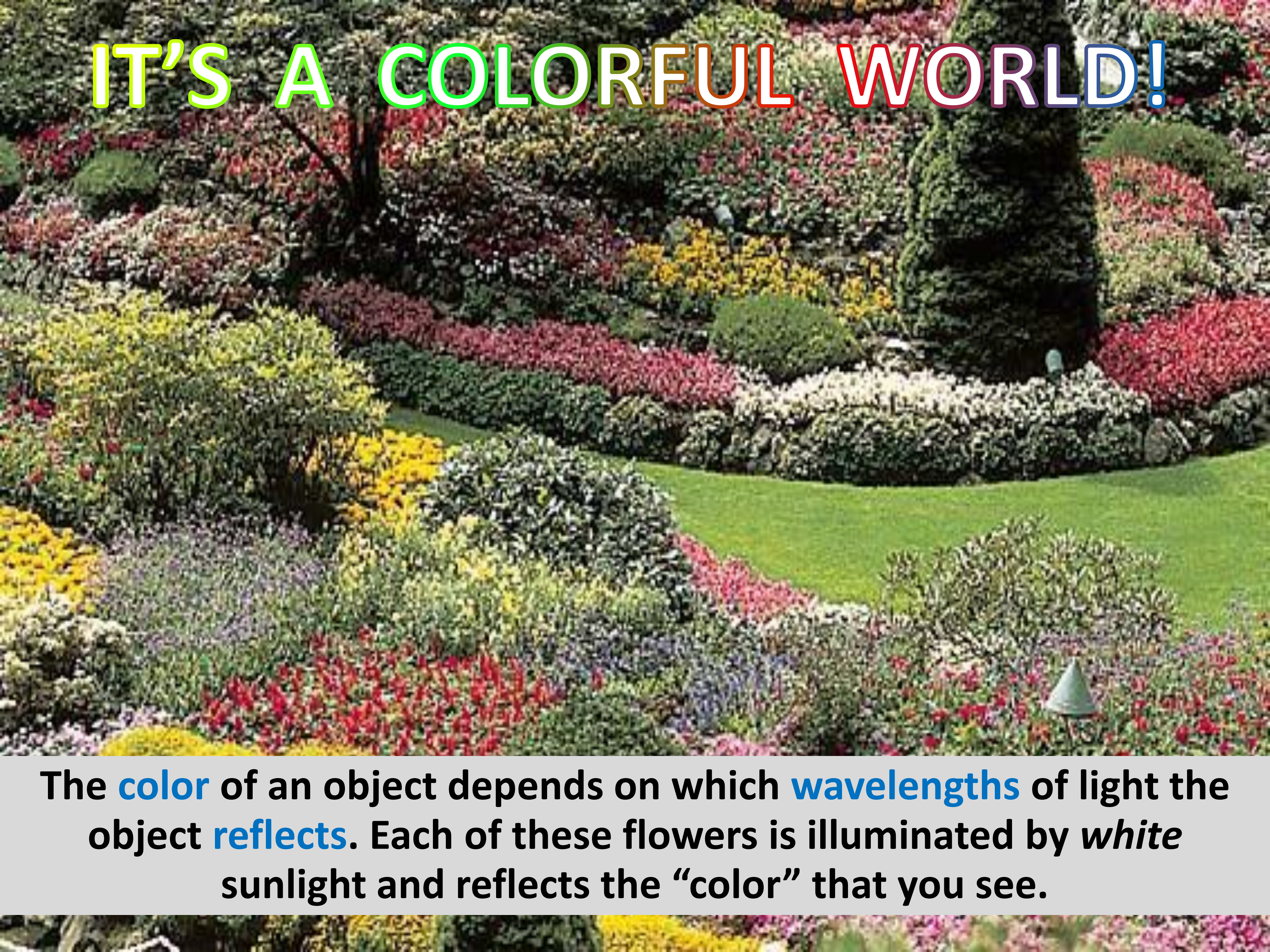
- **Scattering is due to localized non-uniformities *(scattering centers)* in the medium through which light passes.**
- **The most critical factor is the <u>scattering centers size relative to the wavelength of the light</u> being scattered.**
- **Amount of the scattered light can strongly depend on the wavelength of light.**

I See Skies of Blue…



…and Red Sunsets too!

IT'S A COLORFUL WORLD!



The color of an object depends on which wavelengths of light the object reflects. Each of these flowers is illuminated by *white* sunlight and reflects the "color" that you see.

Similarly,

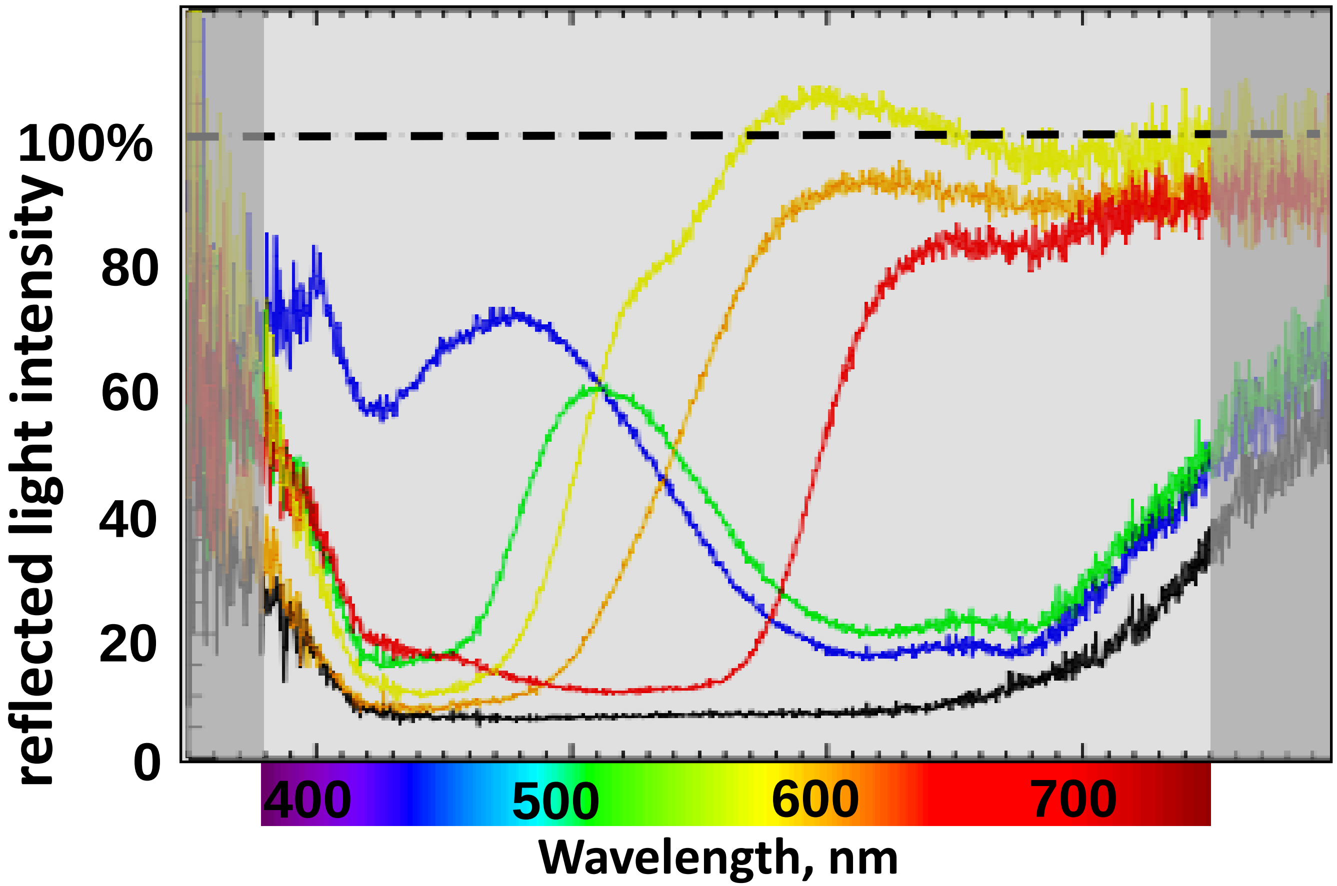
each of these colored paper fans is illuminated by *white* light and reflects the color that you see.

color is defined by wavelength

Let's measure it!

Reflected Light Spectrum

“How much of each color bounces off?”



***Selective reflection* of sunlight off colored paper fans,**

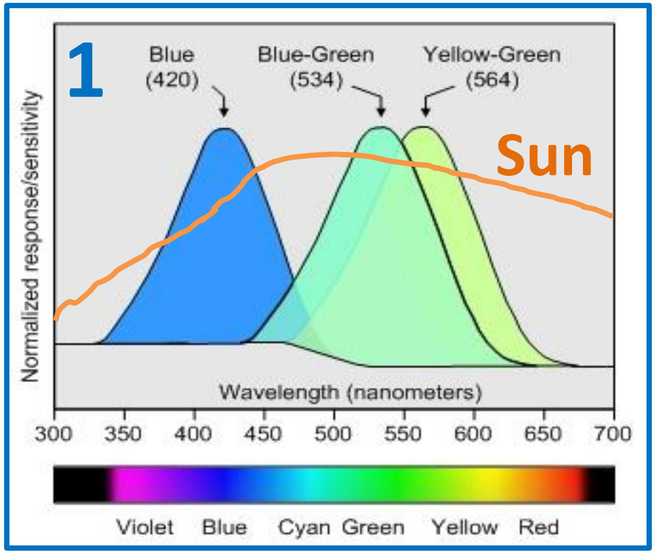
blue
green
yellow
orange
red
black.

Question: what would a white paper curve look like?

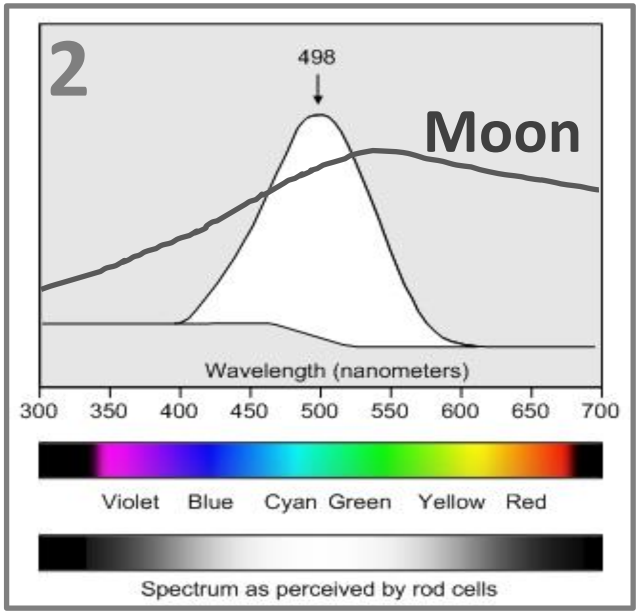
…and what about that pink fan?

... so how do we see color?

The brain perceives color based on two major light detectors in the eye:



1. **Cone cells detect color**
   - each type of cone cell absorbs specific colors (wavelengths) of light
   - the number of cone cell types creates the range and detail of color an eye can see (distinguish).

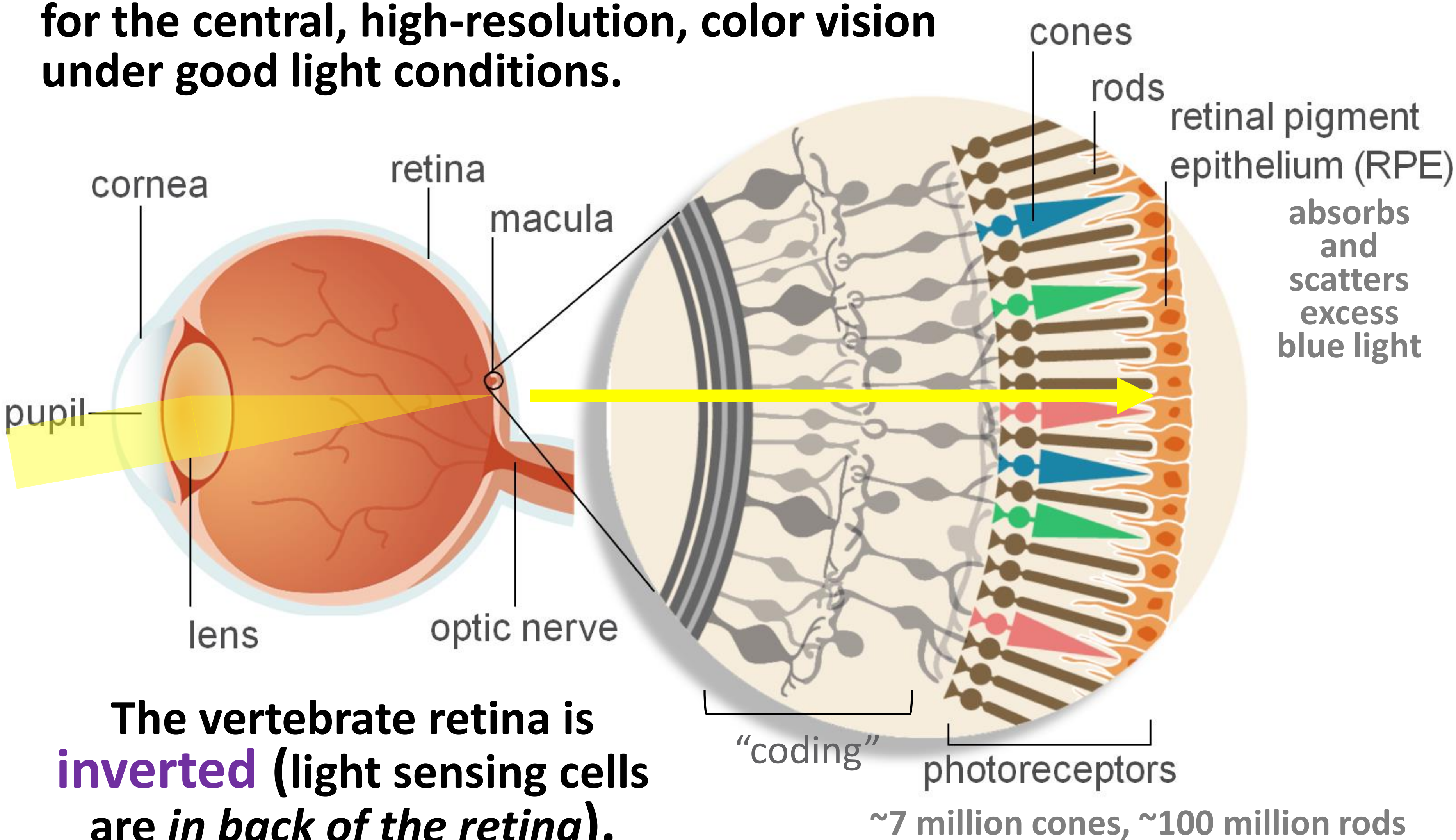


2. **Rod cells detect intensity**
   - shades of a color (either light or dark)
   - ~1000x more sensitive than cone cells
   - maximum sensitivity at ~500 nm
   - retina contains about 20 times more rods than cones.

Photopic vision – bright light, cones.
Scotopic vision - in the dark, rods.

Human Eye Structure

The macula has high concentration of cones and is responsible for the central, high-resolution, color vision under good light conditions.

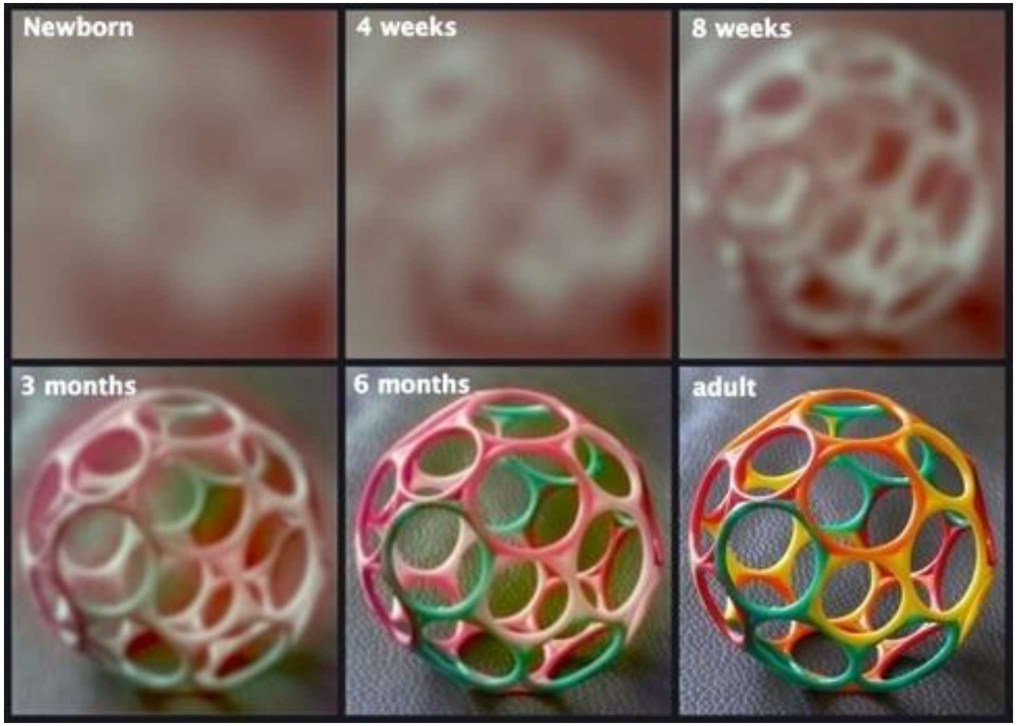


The vertebrate retina is inverted (light sensing cells are *in back of the retina*).

Learning Process

Our visual abilities such as focusing (accommodation), moving the eyes accurately (eye tracking), using the eyes together (eye teaming), and the brain processing what it sees (visual processing including color recognition) are learned skills.

- At birth, we can only see as far as 7-10 inches away and in two dimensions only.
- By 1 month, the useful sight distance grows to about 3 feet, depth perception and 3D vision begin to appear.
- By 6 month, vision is almost fully developed, clarity and sharpness close to an adult.



By ~3 years of age complete development of color vision is achieved.

Do you see what I see?

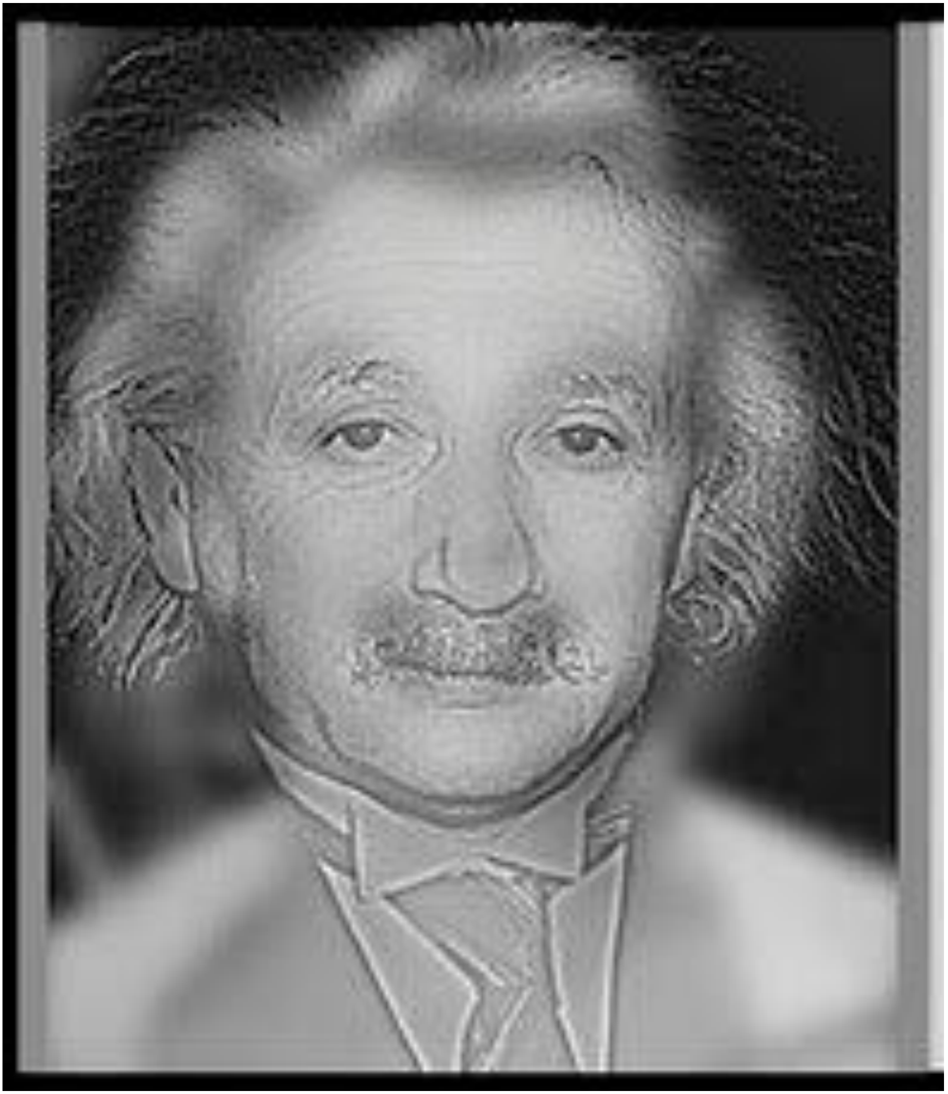
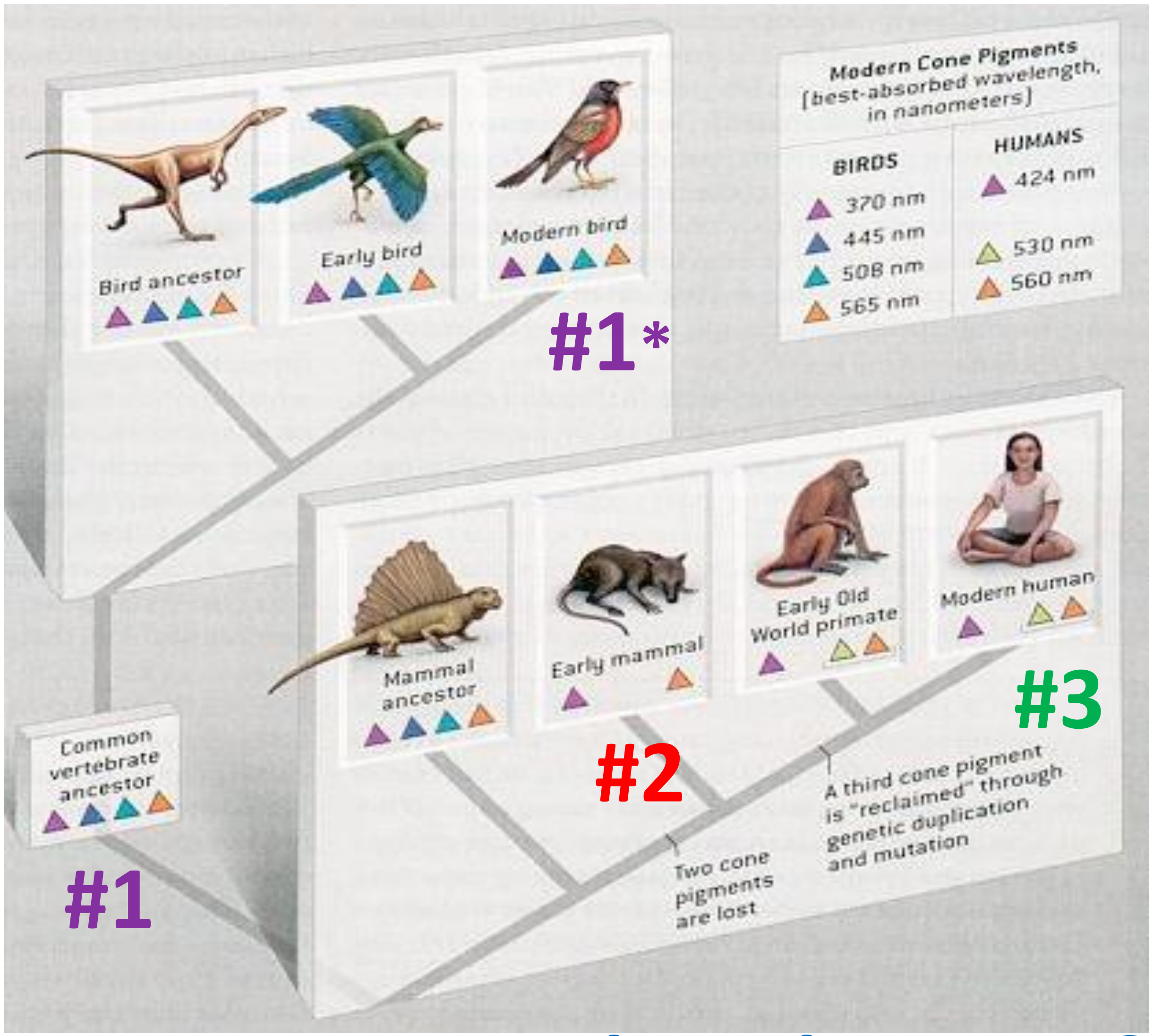
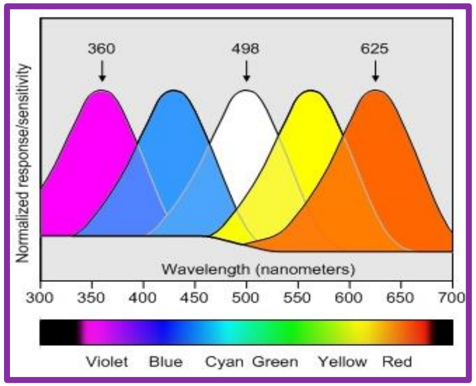


Image recognition
is based on
current observation
and
prior information.

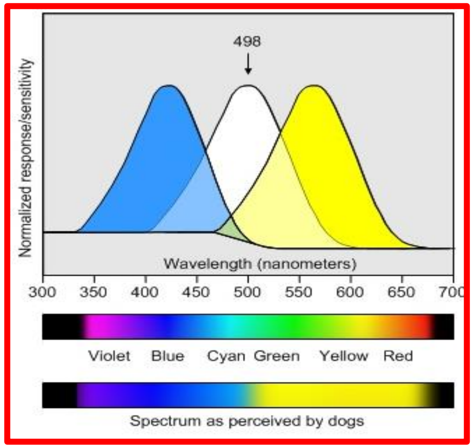
It is another
very important
***learned skill*!**

Evolution of Color Vision

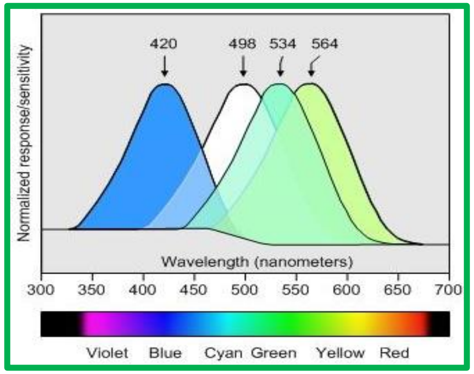




#1



#2



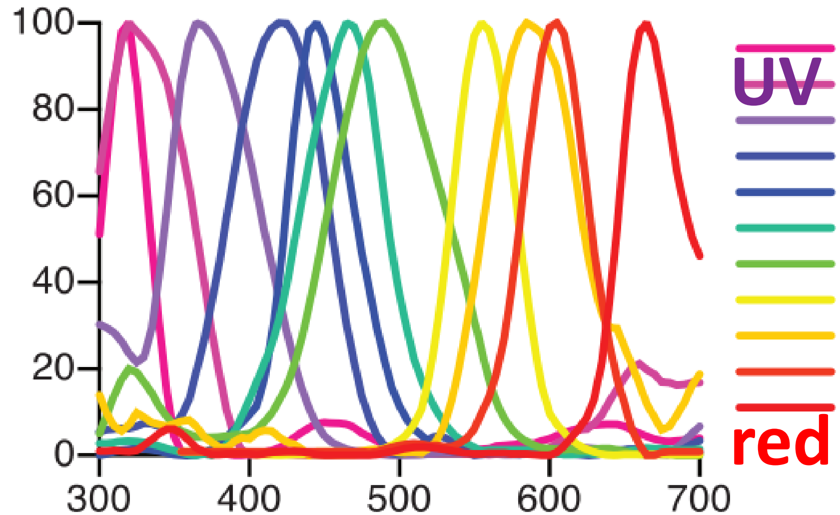
#3

Can there be more?

Mantis shrimp has 12 distinct photoreceptor types!

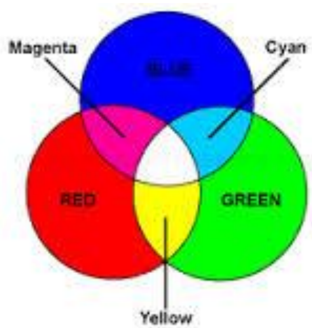
- There are more than 500 known species of mantis shrimp, which range in size from less than an inch to over a foot long.
- They mainly live among the coral reefs of tropical oceans — one of the most colorful environments on Earth.
- The mantis shrimp eyes are considered to be the most complex eyes in the animal kingdom.

- With its 12 cones, the mantis shrimp is able to immediately recognize basic colors just by scanning an object with their eyes, rather than using the brain to distinguish different colors of light.
- While it can make quick and reliable determinations of basic color, the creature is rather bad at discriminating close colors from one another.



Color Formation

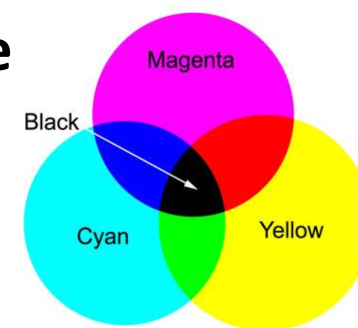
- The three color receptors in the human eye allow us to see millions of different colors.
- Color formation mechanism in the eye is <u>additive</u>.
- The additive primary colors are red, green, and blue (RGB).



- All the <u>different hues</u> of color that we see can be made by changing the <u>proportions</u> of red, green, and blue <u>light</u>.

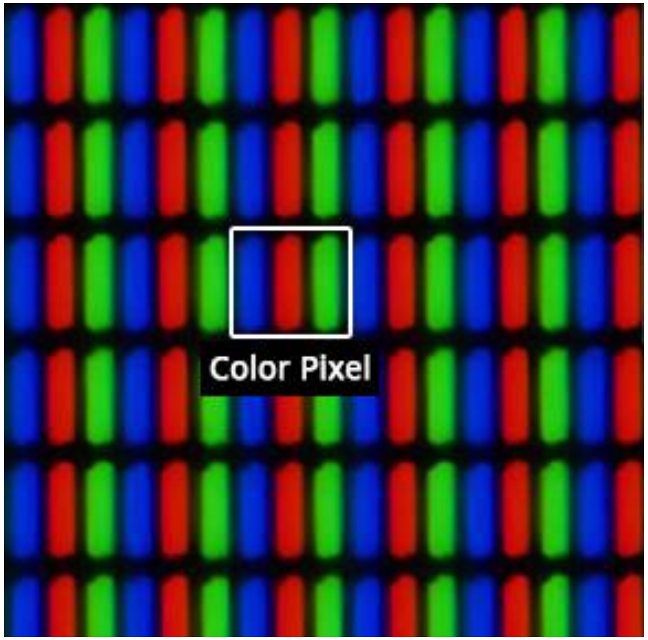
Mixing light is <u>additive</u>.

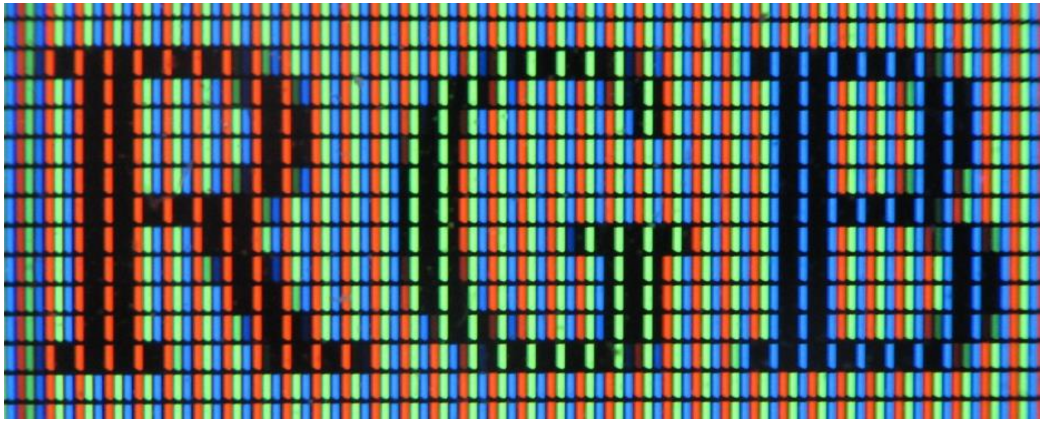
- Inks, dyes, and paints get their color from a <u>subtractive process</u>.
- Chemicals, known as pigments, <u>absorb some colors</u> (that is, *subtract from white light*) and <u>allow the rest to be reflected</u> – this reflected light makes the color you actually see.
- The subtractive primary colors are cyan, magenta, and yellow (CMY).



Mixing paints or pigments is <u>subtractive</u>.

...computer screen IN DETAIL

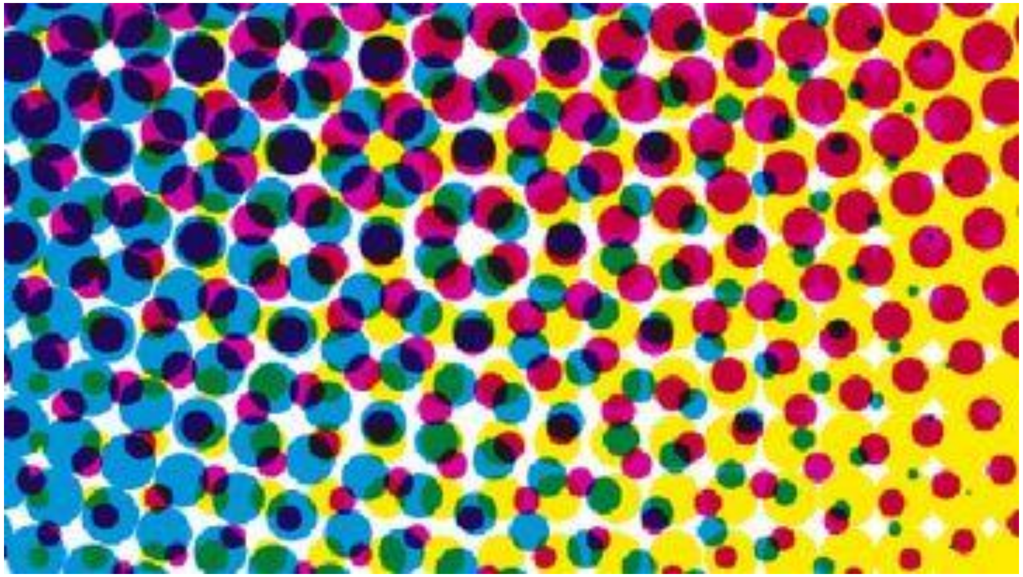




good screens have about 100-200 PPI

...something printed

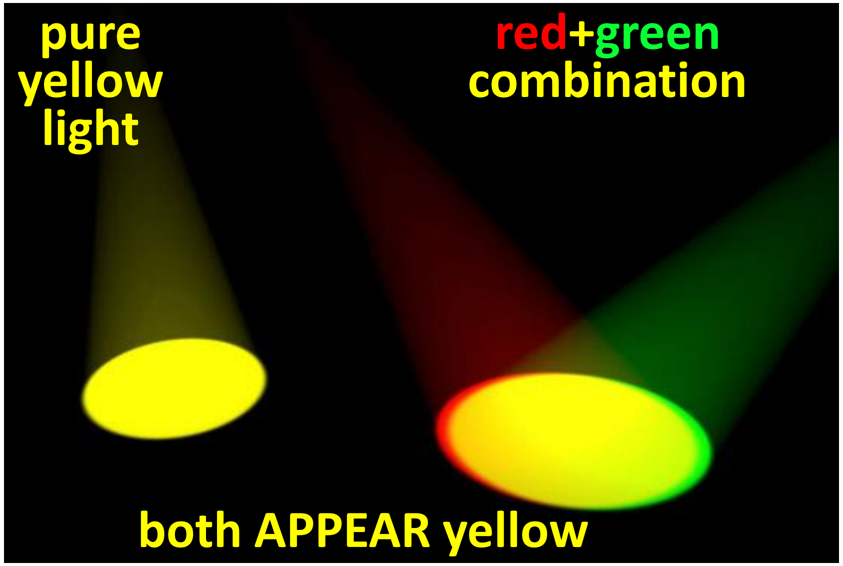
IN DETAIL



Is Color *Real*?

Additive color mixing is subjective – it provides only the sensation of color.

- **Actual wavelength may not be present within the combined spectra of the incoming light.**
- **For the eye-brain system, there is no difference between *pure yellow* light and *red-green combination*.**



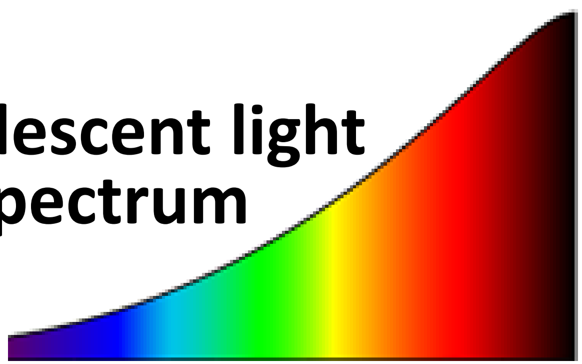
- **What about PINK? MAGENTA? PURPLE?**
- **<u>Combination colors</u> – do not exist within the spectrum of white light, but are recognized as distinct colors by human visual system.**

…actually, all "colors" we see could be considered a trick of the mind ☺

What color is this tulip? And why?

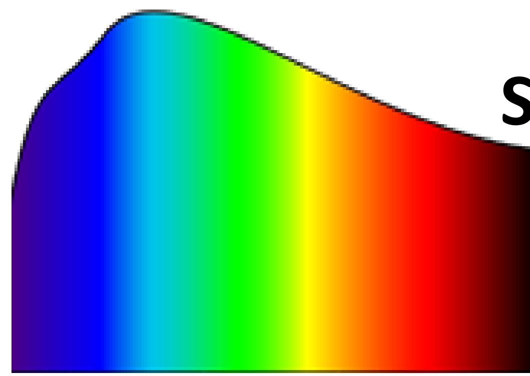
Indoor and outdoor *lighting* can be quite different!

Incandescent light bulb spectrum



much more red+yellow than blue

Sunlight spectrum



red and blue components are similar