

Please pick up your 2nd midterm from front of class if you haven't already

Looking ahead:

- **Tues May 22:** Final Exam, 11.30am – 1.30pm, 65 multiple-choice questions
- **Final Exam is cumulative** i.e. Chs. 2, 3, 4, 5, 6, 7, 8, 9, 11, 13, 14, 15, 19, 20, 22, 23, 24, 25, 26, 27, 31

Today:

Chapter 27 (**C**olor)
Teacher evaluations

Color: What gives an object color?

First, recall simple model of atom and what light does to atoms in **Ch. 26**:

There are natural frequencies associated with electron vibration - different for different atoms/molecules.

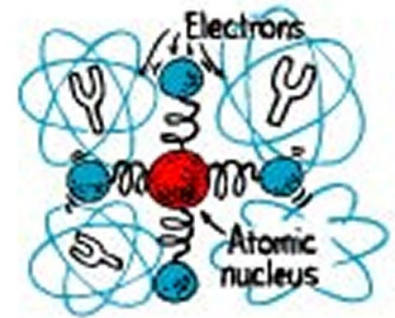
Light of certain frequency impinging on material forces vibrations of electrons at that frequency

If resonant (i.e. = natural freq), material **absorbs** the light turning it into heat.

If off-resonant, atoms re-emit the original frequency:

transparent materials **transmit** the light

opaque materials **reflect** the light



From last time

➤ The color comes from those frequencies that are reflected, i.e. off-resonant in the visible spectrum: **“Selective reflection”**

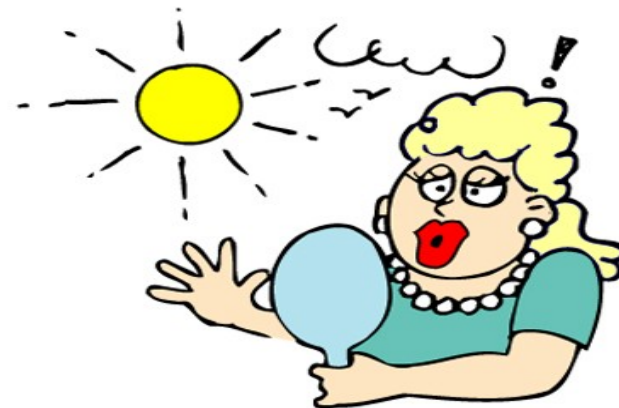
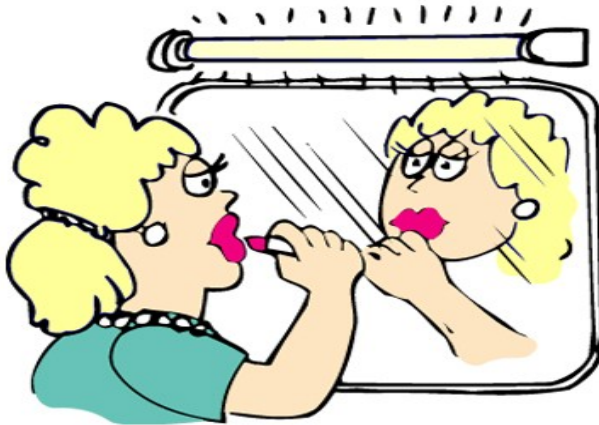
Selective Reflection

- Usually, a material absorbs light of some frequencies, and reflects the rest
usually a spread of freqs
- Eg. A red rose:
 - petal appears red since petal's atoms absorb all visible light frequencies *except* red, which it reflects. (i.e. blues, greens are resonant).
 - But, if hold rose in green (or blue) light, then the petal looks black – since all the impinging frequencies are resonant, so get absorbed.
- i.e. Apparent color of object depends not only on what's not its natural frequencies, but also on what is illuminating it.

Selective Reflection cont.

- Eg. incandescent vs fluorescent light bulb – both emit all frequencies, but incandescent emits more at the lower frequencies (i.e red) and fluorescent emits more of the higher freqs (i.e blue). So:

Fluorescent light here – enhances blues, plays down reds, so lipstick looks less red (pink) c.f. in sunlight !

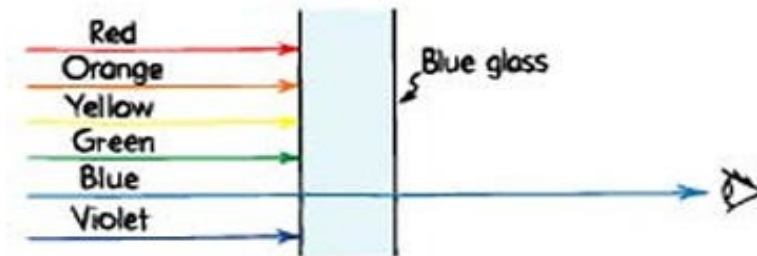


Selective Transmission

- Similarly, color of transparent object determined by what frequencies are non-resonant
- Eg. Blue glass appears blue because all other frequencies illuminating it coincide with natural frequencies of the atoms in the *pigment* (dye), so get absorbed:

are fine particles that selectively absorb certain freqs & transmit others

blue glass is transparent to blue, i.e. off-resonant in blue-frequency range



Question

Why does a blue glass feel slightly warmer to touch than usual colorless window glass?

Because blue glass absorbs the other visible-range frequencies, transforming their energy to random kinetic energy of the glass molecules i.e. heat. Colorless glass means that all frequencies in the visible range get transmitted (none are resonant) i.e. none get absorbed.

Clicker Question

When green light is shone on a red rose, what happens ?

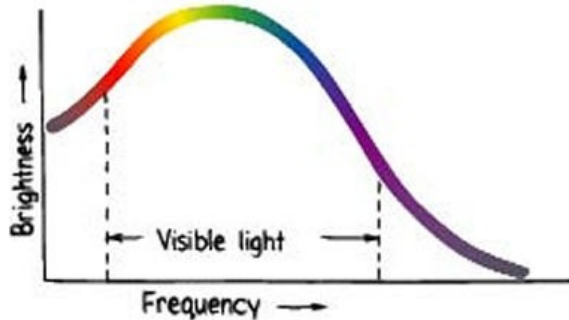
- A) The leaves become warmer than the petals
- B) The petals become warmer than the leaves
- C) Both petals and leaves warm up the same amount

Answer: B

Because green is absorbed by the red petals, turning the light energy into heat. (The petals appear black). The leaves, on the other hand, reflect green.

Mixing colored light

- White light from the sun is composed of all the visible frequencies - as demonstrated by a rainbow, or passing it through a prism.
- Intensity of light varies with frequency - “**Radiation curve**” of sunlight is:



- Most intense in the yellow-green.

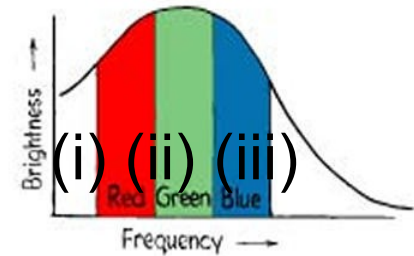
- Our eyes have evolved to have max sensitivity in yellow-green!

- That's why fire-engines & school-buses are now painted yellow-green, and why use yellow sodium-vapor street lamps at night.

Mixing colored light cont.

- All colors combine to make white
- In fact, just red (R) + green (G) + blue (B) is perceived as white too.

Why?



Recall 3 types of cones (color receptors) in eye :

- (i) Stimulated by **lowest** 1/3 of spectrum - light of these frequencies appears **red**
- (ii) “ “ **middle** “ “ “ “ “ **green**
- (iii) “ “ **highest** “ “ “ “ “ **blue**

When all 3 types of cones stimulated equally, we perceive white.

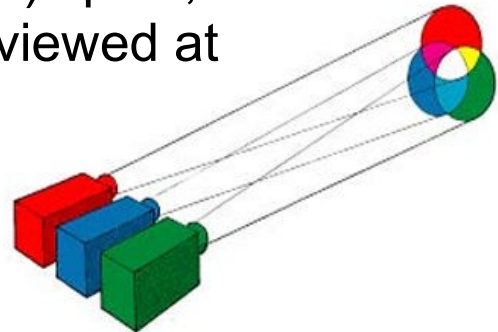
Mixing colored light cont.

In fact, *any* color in the spectrum can be produced by various amounts of **red**, **green** and **blue**: these are called the **additive primary colors**

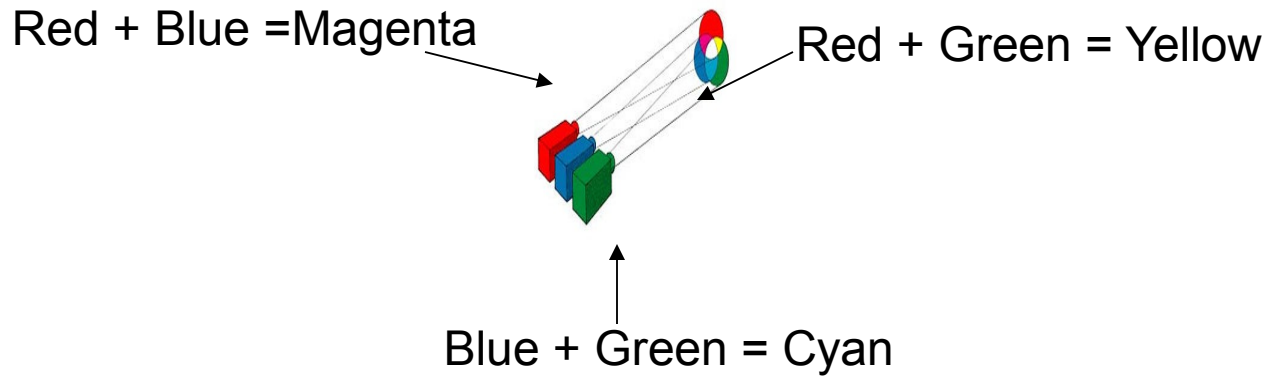
Eg. Project red, blue, green lamps on screen:

Where two colors overlap, another is produced. We say they the two “add” to each other.

(This is what’s going on in a color tv – tiny (<mm) spots, either R, B or G; gives a range of colors when viewed at a distance)



Adding colors...



Since $R + B = \text{magenta}$, and $R+B+G = \text{white}$, then $\text{magenta} + \text{green} = \text{white}$.

Magenta and green are called **complementary colors**: i.e. Two colors that add together to make white.

So, complementary pairs are:

- Magenta and Green
- Yellow and Blue (since $\text{Yellow} = (R+G) + B$)
- Cyan and Red

Clicker Question

If sunlight were green instead of white, the most comfortable color to wear on a cold (but sunny) day would be:

A) yellow

B) blue

C) green

D) magenta

E) violet

Answer: D, magenta

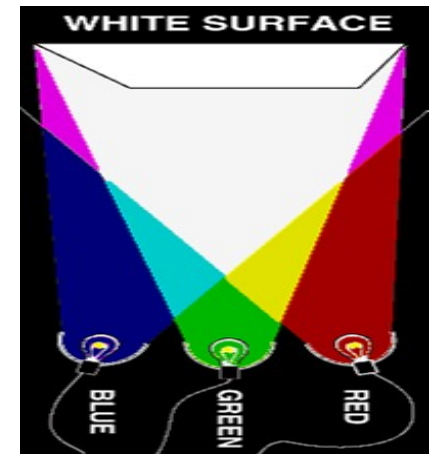
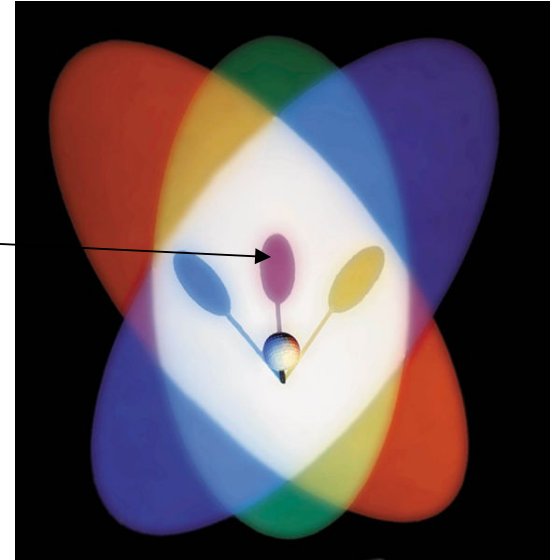
You'd want pigments that absorb the green and turn it into heat. Magenta is the complementary color to green, so absorbs green.

Addition of colors used in lighting stage performances – get interesting colored shadows:

Eg. R, G, B, colored lamps illuminating a golf ball:

Ball appears white (= R+G+B).

· This middle shadow is cast by the green lamp. If the red and blue lamps were turned off, this shadow would be black. But instead it is illuminated by the R and B lamps, which add to magenta.



Similarly, can explain - the cyan shadow cast by the red lamp (lit by G and B lamps)

- the yellow shadow cast by the blue lamp (lit by R and G lamps)

Clicker Question

If ball was bigger so that shadows from each lamp overlapped, what would be the color of the shadow directly behind the ball?

- A) White
- B) Green – the color of the middle lamp
- C) Magenta – white minus green
- D) Black
- E) None of the above

Answer: D

Black – i.e. no color, since that part of ball obstructs light from all three lamps.

Mixing colored pigments

- If $R + B + G = \text{white}$, how come mixing red, blue, and green paints makes a brownish-black?
- It's because you're mixing *pigments*, rather than mixing *lights* directly: pigments **absorb** specific colors,
e.g. A red paint pigment absorbs the complementary color (cyan), and reflects red (see selective reflection earlier)
i.e. this is **color subtraction** – pigment takes away the complementary color (eg cyan) from the impinging light.
- So if you mix red, blue and green pigments, then you are absorbing cyan, magenta, and yellow, i.e. everything. So get black (= absence of color).

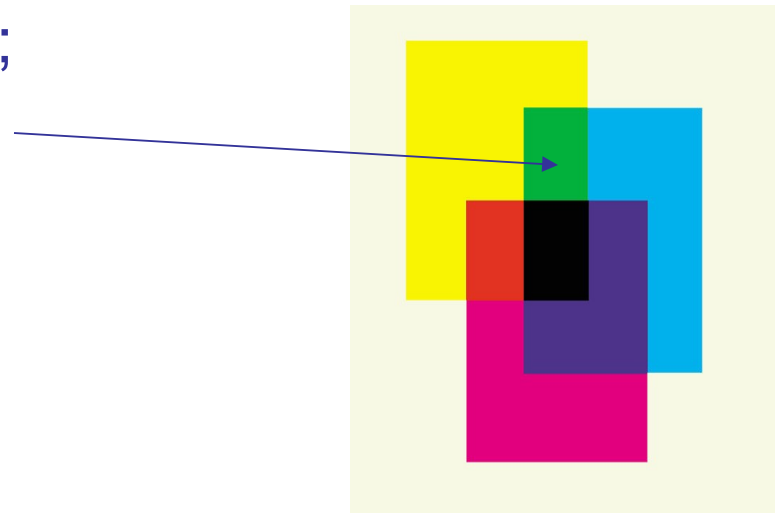
Mixing colored pigments cont.

Subtractive primaries – magenta, cyan, yellow

i.e. the colors obtained from subtracting the additive primaries from white. (ie the complementary colors to those).

Yellow pigment absorbs blue;
cyan absorbs red. So both
absorbed where overlap –
which thus appears (white –
blue – red) = green

Pigments:



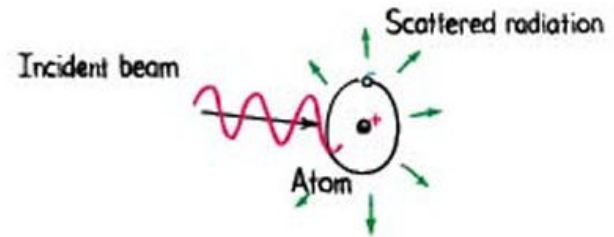
• Colored photos – composed of dots of magenta, cyan, yellow

Why the sky is blue

- Arises from selective **scattering** - *not* from color addition/subtraction
 - i.e. light striking atoms and molecules in a gas (ie far apart from each other) gets re-emitted in many directions.

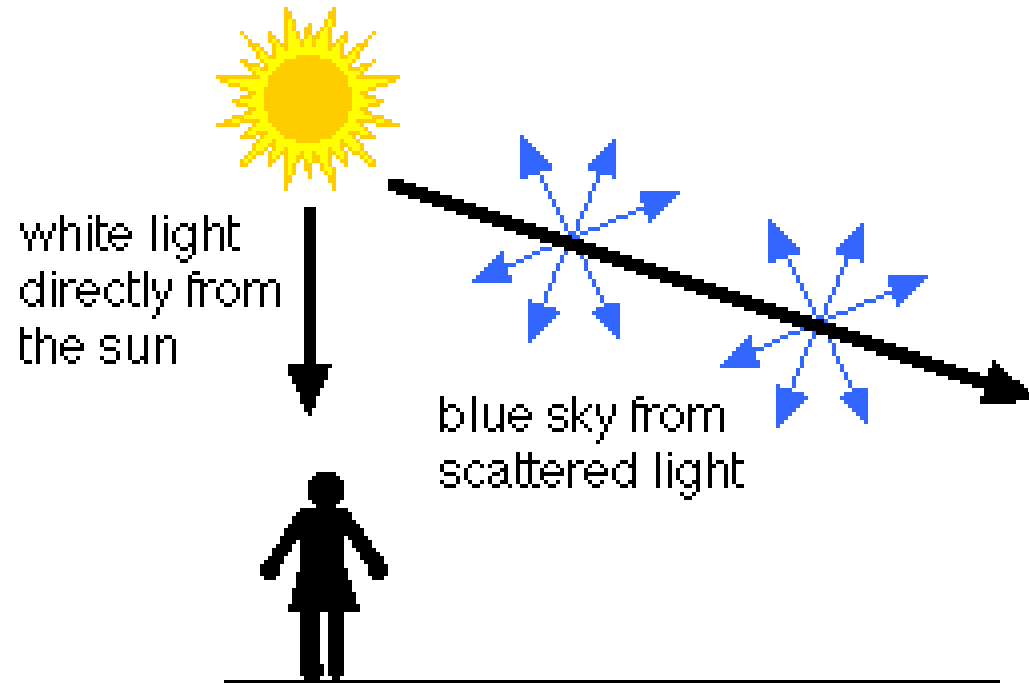
← i.e. *scattered*

- The *tinier* the particle, the more *higher-frequency* light it will re-emit
(*c.f.* sound vibrations – smaller bells have higher pitch than larger bells)
- N₂ and O₂ in atmosphere are like such tiny bells.



So, what does this mean for the sky? Next slide...

Why the sky is blue cont.



· So, as light moves through atmosphere, most goes in straight lines, but when it hits a molecule, the higher freqs (violet, blue) especially get scattered in all directions.

i.e. blue reaches you in any direction you look - you see blue light from everywhere overhead –

i.e. a blue sky !

Why the sky is blue cont.

- But violet is higher freq than blue – why don't we see a violet sky?

We would if our eyes were equally sensitive to violet and blue, but the cones in our eyes sense blue much more, so we sense a blue sky.

Other creatures with better violet vision like bumble bees, do see a violet sky!

- The lower freqs pass more or less in a straight line; e.g. red scatters a tenth as much as violet.
- **DEMO:** shine flashlight through water with a few drops of milk in it. View from the side, see bluish haze. If look straight through, see reddish-orange – as this doesn't get scattered so much. *Remember this demo when we get to sunsets!*

Why the sky is blue cont.

- Why are some skies bluer than others?

Depends on what's in the atmosphere, i.e. How much water, dust, etc - these particles are larger than O₂, N₂, so scatter lower freqs strongly as well, making sky less blue and more whitish.

e.g. Drier atmospheres (eg in Greece and Italy) have deeper blue skies than more humid ones

e.g. Polluted cities – even greyish skies, because of exhaust gases absorbing rather than scattering...

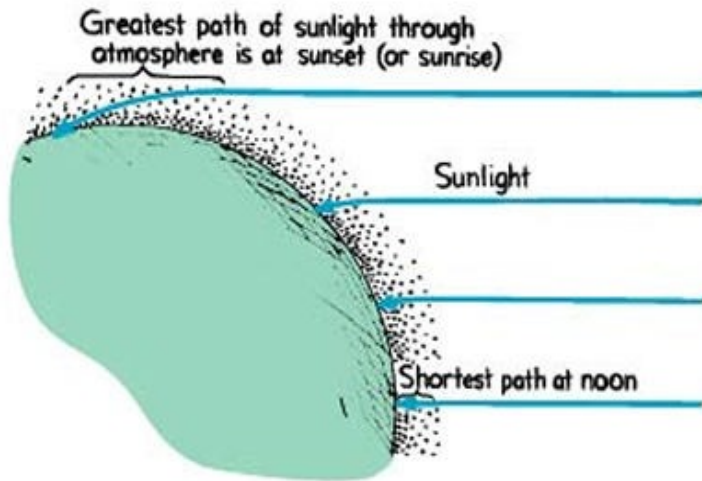
Why sunsets are red

- Light that's not scattered is light that is transmitted i.e. reds-oranges especially.
- **E.g. Previous DEMO** – front view of flashlight through milky-water.
- The thicker the atmosphere the light passes through, the more of the higher-freqs that will be rescattered away from the transmitted beam, i.e. the transmitted beam is redder (...next slide)

Why sunsets are red cont.

This is what happens at sunsets (or sunrises) :

Red-orange sunset, as almost all higher freqs scattered away.



As day progresses, more blue/violet scattered, as sunlight travels greater dist through atmosphere, so sun looks increasingly orange.

- Note consistency with color mixing rule: white – blue/violet = yellow/orange sun
- At sunset, medium-freq green is also subtracted, just red remains. ($W = R + \cancel{B} + \cancel{G}$)

Clicker Question

If molecules in the sky instead scattered low-frequency light more than high-frequency light, what color would the sky be? What color would sunsets be?

- A) The sky would still be blue, sunsets still reddish-orange
- B) The sky would be reddish-orange, sunsets blue
- C) Both with would blue
- D) Both would be reddish-orange
- E) None of the above

Answer: B

The day-time sky would have low-frequencies, ie reddish-orange. The sunsets would be white-minus-these, i.e. blue!

Another Question

Why does smoke from a campfire look blue against trees near the ground but yellow against the sky?

Particles in the smoke scatter mostly blue light, so against a dark background like the trees near the ground, we see the smoke as blue (analogous to sky, with dark beyond earth). i.e. we see the scattered light.

But, against the bright sky, you see mostly the sky-minus-light-scattered from the smoke, i.e. white - blue = yellow.

This is also why the sun looks yellow in the day time!

Clicker Question

Red sunsets are due to lower frequencies of light that

- A) are scattered from larger particles in the air
- B) are refracted from larger particles in the air
- C) are reflected by clouds and relatively large particles in the air
- D) survive being scattered in the air
- E) appear reddish orange to the eye.

Answer: D, survive being scattered in the air.

Recall it is the high frequency blues that are scattered by the atmospheric particles which are relatively small. This leaves orange/red to be transmitted...

Why clouds are white

- First, what *are* clouds?!

A mass of water droplets of various sizes suspended in the atmosphere.

- Different sizes of droplets scatter different freqs - smallest ones scatter high freqs like blue/violet, slightly bigger ones scatter medium freqs like green, and bigger ones scatter reds – hence, net scattered is white!
- If droplets and clouds get too large, get appreciable absorption, so they look darker (greyer).

Why Water is Greenish-Blue

- If look at surface of lake or ocean, it may appear deep blue – but that's because it reflects the sky's blue.

- However, if put white paper under water, it looks pale greenish-blue.

- Why?

Although water is transparent in the visible-light regime, it does absorb *some* red: red light is reduced to $\frac{1}{4}$ of original brightness in 15 m of water.

Since complementary color to red is cyan, this means water is cyan

- Explains why many red crabs look black in deep water.
- Also note, water absorbs strongly in the infrared, which is why sunlight warms water

Some final remarks on color...

- So, generally, the color of things depend on what colors are scattered by molecules and also on what colors are absorbed or reflected by molecules.

Eg. Sky is blue from scattering in atmosphere, and water is blue-green from partial absorption of red.

- Eye-color is interesting:

Blue eyes are blue, not to any pigment, but to scattering by small, widely-separated particles in the irises.

Brown eyes, on the other hand, are brown due to absorption by pigments.