CS-184: Computer Graphics

Lecture #2: Color

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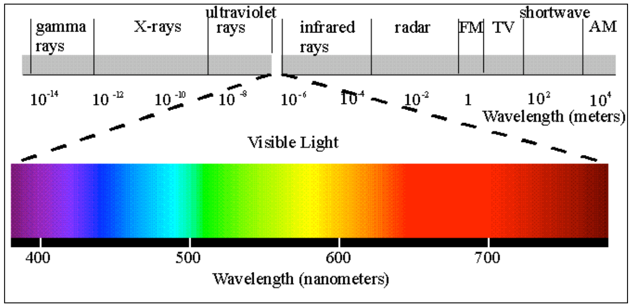
V2009-F-02-1.0

Today

- Color and Light

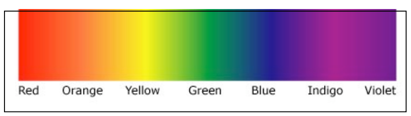
What is Light?

- Radiation in a particular frequency range



Spectral Colors

- Light at a single frequency

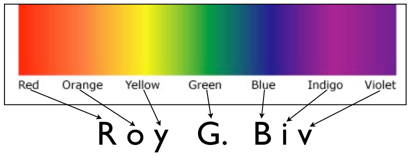


- Bright and distinct in appearance

Reproduction only, not a real spectral color!

Spectral Colors

- Light at a single frequency



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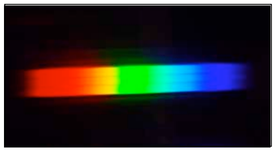


Reproduction only, not a real spectral color!

Other Colors

- Most colors seen are a mix light of several frequencies

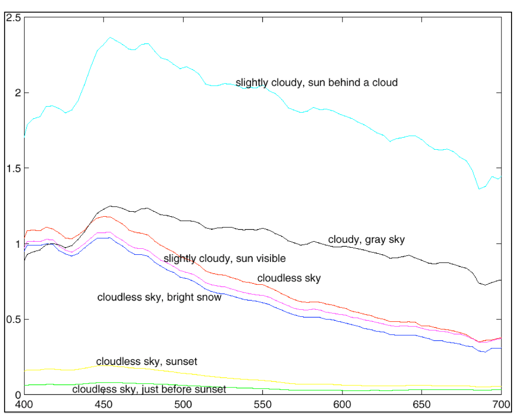
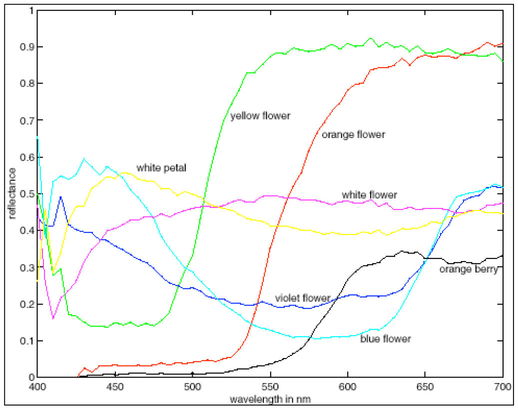


Image from David Forsyth

Other Colors

- Most colors seen are a mix light of several frequencies



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Other Colors

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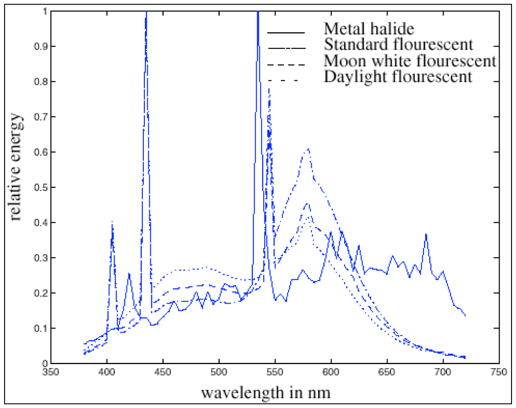
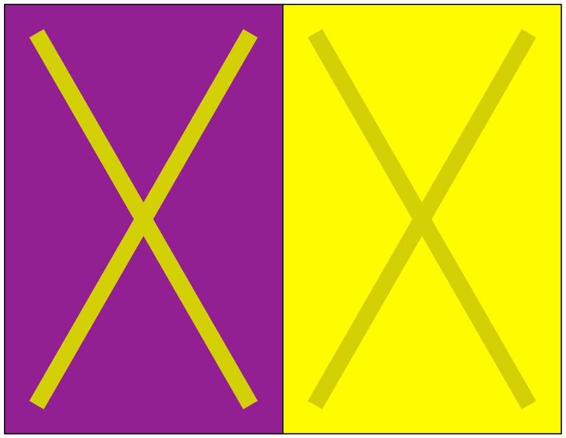


Image from David Forsyth

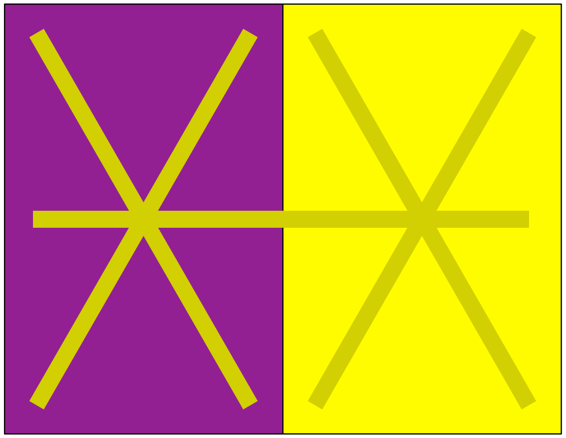
Perception -vs- Measurement

- You do not "see" the spectrum of light
  - Eyes make limited measurements
  - Eyes physically adapt to circumstance
  - You brain adapts in various ways also
  - Weird psychological stuff happens

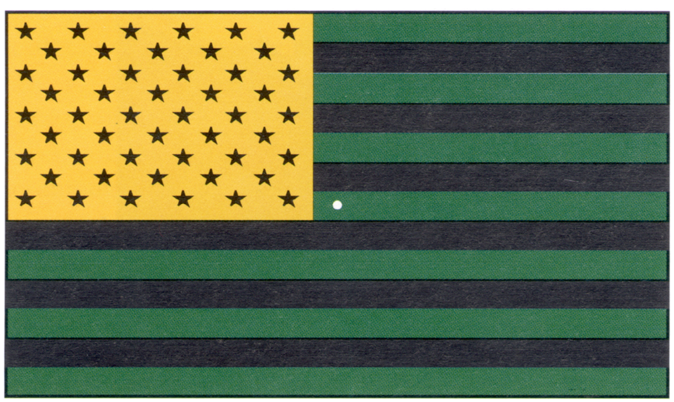
Everything is Relative



Everything is Relative

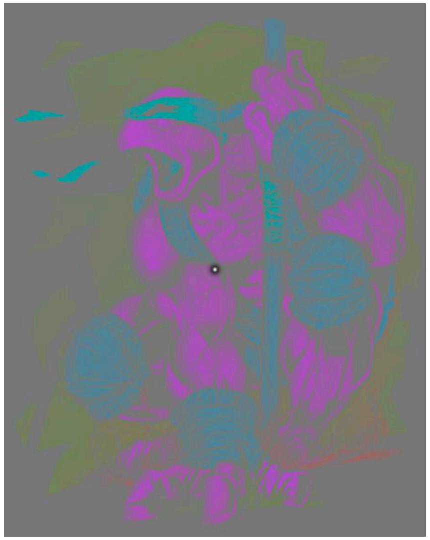


Adapt



Adapt

Adapt



Adapt

It's all in your mind...

XXXXXX	GREEN	GREEN
XXXXXX	BLUE	BLUE
XXXXXX	YELLOW	YELLOW
XXXXXX	PURPLE	PURPLE
XXXXXX	ORANGE	ORANGE
XXXXXX	RED	RED
XXXXXX	WHITE	WHITE
XXXXXX	PURPLE	PURPLE
XXXXXX	ORANGE	ORANGE
XXXXXX	BLUE	BLUE
XXXXXX	RED	RED
XXXXXX	GREEN	GREEN
XXXXXX	WHITE	WHITE
XXXXXX	YELLOW	YELLOW
XXXXXX	PURPLE	PURPLE
XXXXXX	RED	RED
XXXXXX	GREEN	GREEN
XXXXXX	BLUE	BLUE

Mach Bands

Mach Bands

Everything's Still Relative

Everything's Still Relative

Eyes as Sensors

- The human eye contains cells that sense light
  - Rods
    - No color (sort of)
    - Spread over the retina
    - More sensitive
  - Cones
    - Three types of cones
    - Each sensitive to different frequency distribution
    - Concentrated in fovea (center of the retina)
    - Less sensitive

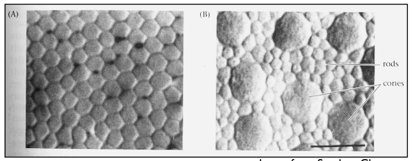


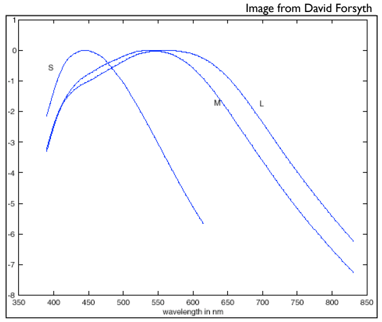
Image from Stephen Chenney

Cones

- Each type of cone responds to different range of frequencies/wavelengths
  - Long, medium, short
  - Ratio: L10/M40/S1
- Also called by color
  - Red, green, blue
  - Misleading:
    "Red" does not mean your red cones are firing...

Note: Rod response peaks between S&M

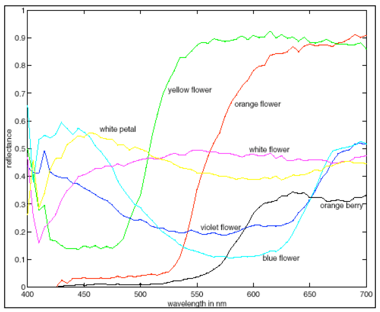
Image from David Forsyth

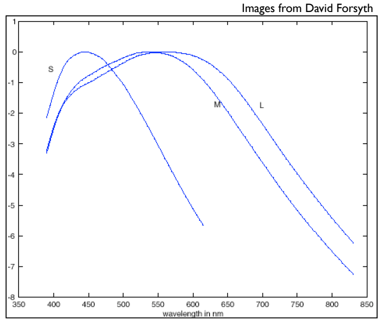


Cones

- Response of a cone is given by a convolution integral :

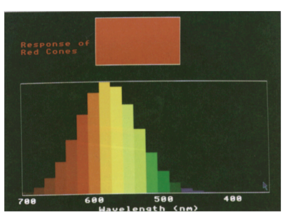
$$r(L,S) = \int L(\lambda) \cdot S(\lambda) \mathrm{d}\lambda$$

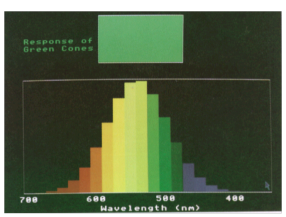


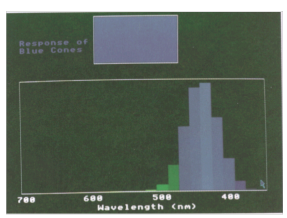


Images from David Forsyth

Cones







Images from David Forsyth

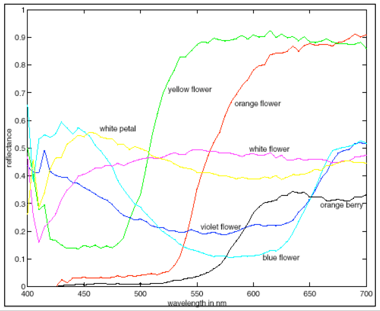
- You can see that “red” and “green” respond to more more than just red and green...

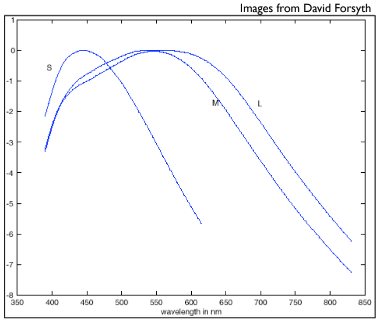
Cones (repeat)

- Response of a cone is given by a convolution integral :

$$r(L,S) = \int L(\lambda) \cdot S(\lambda) \mathrm{d}\lambda$$

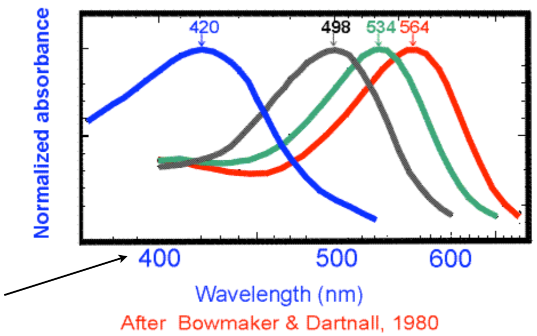
Images from David Forsyth





Rods

- Rods are not uniform across visible spectrum
- Explains why red light is good for night visions



Note the non-uniform scaling on axis!

Cones (repeat)

- Response of a cone is given by a convolution integral :

$$r(L,S) = \int L(\lambda) \cdot S(\lambda) \mathrm{d}\lambda$$

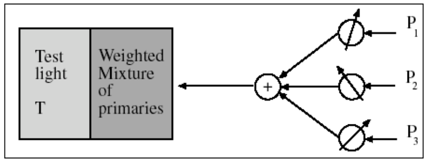
- Different light inputs (L) may produce the same response (r) in all three cones
  - Metamers: different "colors" that look the same
  - Can be quite useful...
  - Odd interactions between illumination and surfaces can be odd...

Trichromaticity

- Eye records color by 3 measurements
- We can "fool" it with combination of 3 signals
- Consequence: monitors, printers, *etc*...

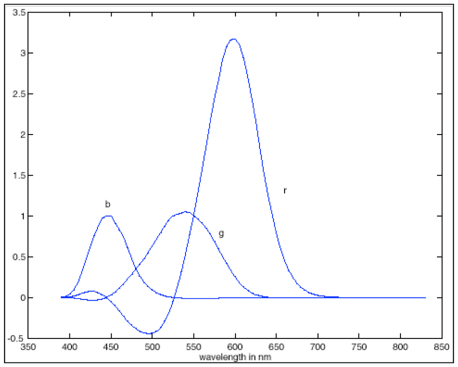
- PS: The cone responses are linear

Additive Color



- Show color on left
- Mix "primaries" on right until they match
- The primaries need not be RGB

Color Matching Functions



- For primaries at 645.2, 526.3, and 444.4 nm
- Note negative region...

Additive Mixing

- Given three colors we agree on
- Make generic color with $M = \alpha A + \beta B + \gamma C$
- Negative not realizable
- Color now described by α, β, γ
- **If** we match on A, B, C
- Example: computer monitor [RGB], paint

Subtractive Mixing

- Given three colors we agree on
- Make generic color with $M = W - (\alpha A + \beta B + \gamma C)$
- Max limited by W
- Color now described by α, β, γ
- **If** we match on A, B, C
- Example: ink [CMYK]

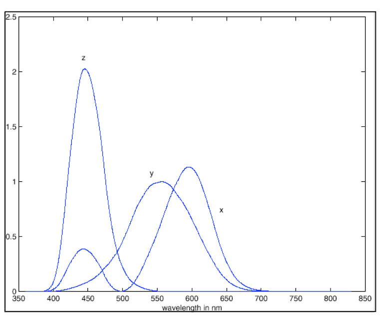
Why 4th ink for black?

CIE XYZ

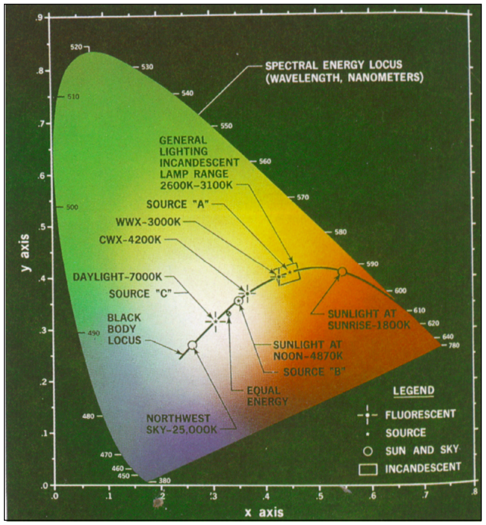
- Imaginary set of color bases
- Match across spectrum with positive values
- X, Y, Z
- Normalized:

  $x = X / (X+Y+Z)$

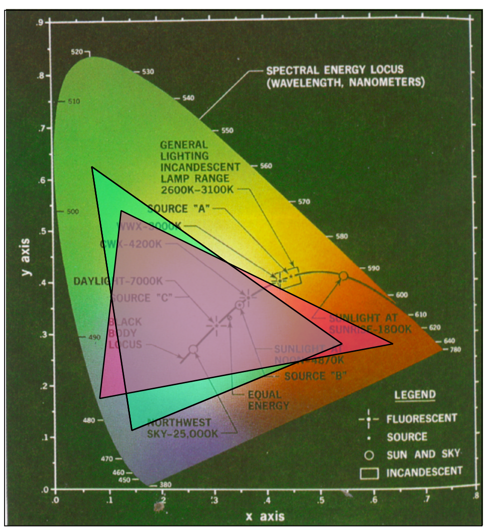
  $y = Y / (X+Y+Z)$



CIE Color Horseshoe Thinggy



Gamuts



Constraints on additive/subtractive mixing limit the range of color a given device can realize.

Devices may differ.

Matching between devices can be difficult.

Dynamic Range

- Max/min values also limited on devices
  - “blackest black”
  - “brightest white”

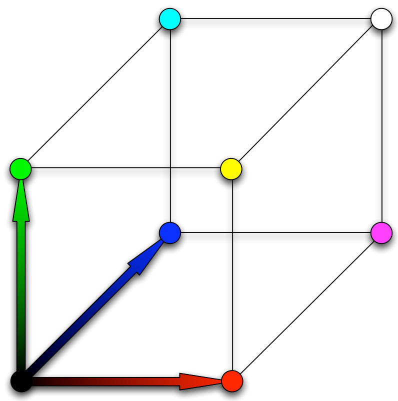
Jack Tumblin

Tone Mapping

“Day for night”
(not the best example, done in Photoshop)

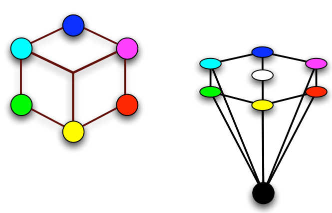
Color Spaces

- RGB color cube



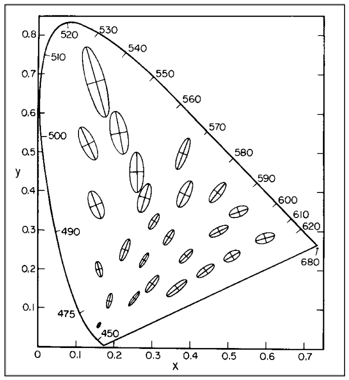
Color Spaces

- RGB color cube
- HSV color cone



Color Spaces

- RGB color cube
- HSV color cone
- CIE

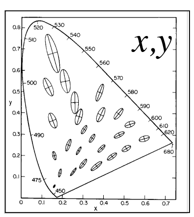


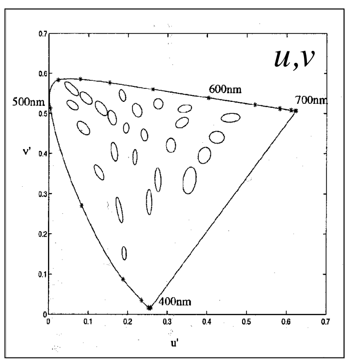
MacAdam Ellipses (10x)

Colors in ellipses indistinguishable from center.

Color Spaces

- RGB color cube
- HSV color cone
- CIE (x,y)
- CIE (u,v)





Scaled to be closer to circles.

$$\begin{bmatrix} u' \\ v' \end{bmatrix} = \frac{1}{X + 15Y + 3Z} \begin{bmatrix} 4X \\ 9Y \end{bmatrix}$$

Color Spaces

- RGB color cube
- HSV color cone
- CIE (x,y)
- CIE (u,v)
- CMYK
- Many others...

Color Phenomena

- Light sources seldom shine directly in eye
- Light follows some transport path, *i.e.:*
  - Source
  - Air
  - Object surface
  - Air
  - Eye
- Color effected by interactions

Reflection

- Light strikes object
- Some frequencies reflect
- Some adsorbed
- Reflected spectrum is light times surface
- Recall metamers...

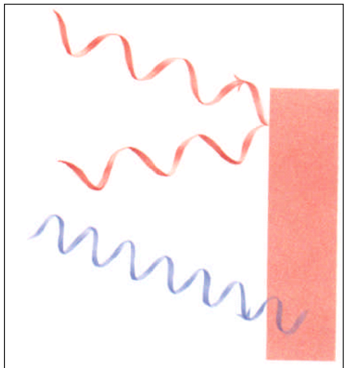


Fig. 1.18 Reflection: red light bounces off an opaque red object, while light of other colours is absorbed.

Unknown?

Transmission

- Light strikes object
- Some frequencies pass
- Some adsorbed (or reflected)

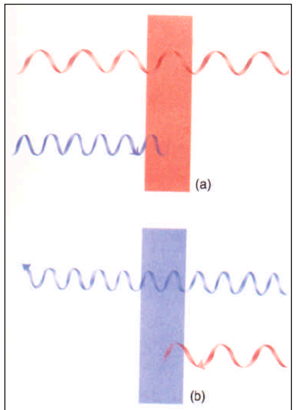


Fig. 1.17 Absorption: a red transparent medium absorbs all wavelengths of light except red (a); a blue transparent medium absorbs all wavelengths except blue (b)

Unknown?

Scattering

- Interactions with small particles in medium
- Long wavelengths ignore
- Short ones scatter

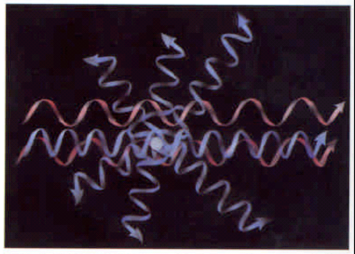


Fig. 1.25 Rayleigh scattering: when particles in air or water are small relative to light wavelength they scatter blue light preferentially.

Unknown?

Interference

- Wave behavior of light
  - Cancelation
  - Reinforcement
- Wavelength dependent

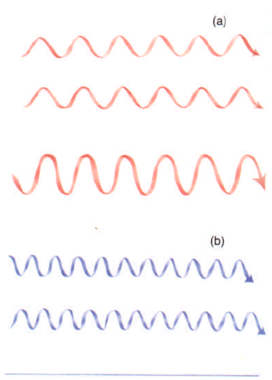


Fig. 1.20 Interference: when two light waves are in phase, they interfere positively to reinforce each other and produce a wave with double the intensity of colour (a). When two waves are out of phase they cancel each other and no colour is seen (b).

Unknown?

Iridescence

- Interaction of light with
  - Small structures
  - Thin transparent surfaces

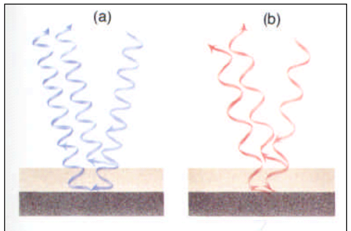
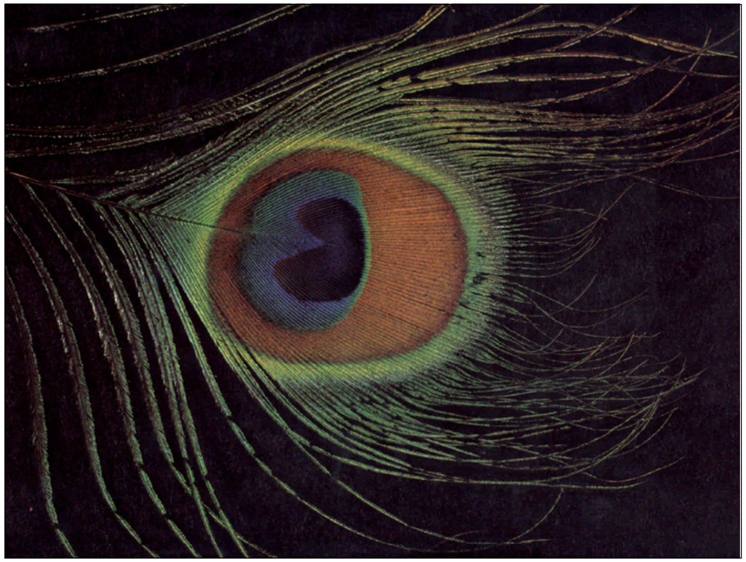


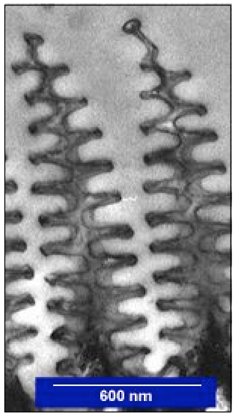
Fig. 1.22 Iridescence: when a light wave is partially reflected and partially transmitted at the surface of a thin layer of transparent material (e.g. a bubble), the two parts of the original wave may interfere with each other when the transmitted wave is reflected from a lower layer and re-emerges at the surface. In this case the blue waves are in phase and their colour is reinforced (a) but the red waves are out of phase and their colour is cancelled (b).

Unknown?

Iridescence



Iridescence



Fluorescence / Phosphorescence

- Photon come in, knocks up electron
- Electron drops and emits photon at other frequency
- May be some latency

- Radio active decay can also emit visible photons

Fluorescence / Phosphorescence

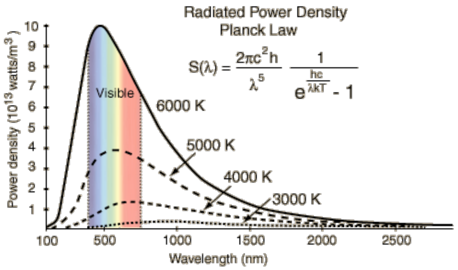
Black Body Radiation

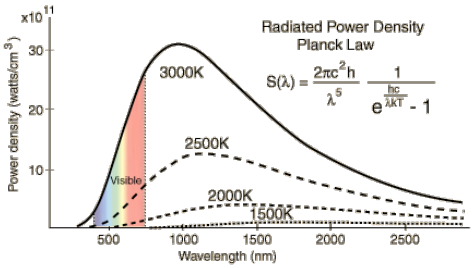
- Hot objects radiate energy
- Frequency is temperature dependent
- Moderately hot objects get into visible range
- Spectral distribution is given by

$$E(\lambda) \propto \left(\frac{1}{\lambda^5}\right)\left(\frac{1}{\exp(hc/k\lambda T) - 1}\right)$$

- Leads to notion of "color temperature"

Black Body Radiation





HyperPhysics